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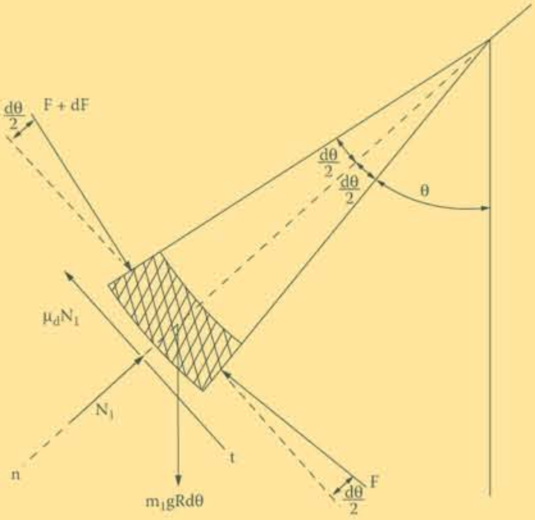

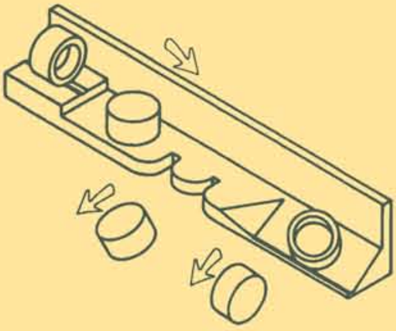

Geoffrey Boothroyd

Assembly Automation and Product Design

Second Edition

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

A Series of Reference Books and Textbooks

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Second Edition

Geoffrey Boothroyd
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Preface

Portions of this book are based on a book published in 1968 under the title *Mechanized Assembly* by G. Boothroyd and A.H. Redford. In a later further edition, titled *Automatic Assembly* by G. Boothroyd, C. Poli, and L.E. Murch, the original material developed at the University of Salford in England was updated with work carried out at the University of Massachusetts. In those days, it was felt that manufacturing engineers and designers wished to learn about automatic assembly as it appeared to provide a means of improving productivity and competitiveness. Since 1978, I developed a subject that holds much greater promise for productivity improvement and cost reduction, namely, design for assembly (DFA). The DFA method has become widely used and has helped numerous companies introduce competitive product designs.

This text, therefore, includes detailed discussions of design for assembly, and the subject of assembly automation is considered in parallel with that of product design.

The first step in considering automation of assembly should be careful analysis of the product design for ease of automatic assembly. In addition, analysis of the product for ease of manual assembly should be carried out in order to provide the basis for economic comparisons of automation. Indeed, it is often found that if a product is designed appropriately, manual assembly is so inexpensive that automation cannot be justified. Thus, a whole chapter is devoted to design for manual assembly. Another chapter is devoted to design for high-speed automatic and robot assembly, and a third chapter deals with electronics assembly.

This second edition includes, as an appendix, the popular *Handbook of Feeding and Orienting Techniques for Small Parts* published at the University of Massachusetts. This edition also includes the original data and coding systems for product design for high-speed automatic and robot assembly also developed at the University of Massachusetts. Finally, numerous problems have been added and worked solutions to all the problems are available.

The book is intended to appeal to manufacturing and product engineers as well as to engineering students in colleges and universities.

I wish to thank Dr. A.H. Redford for his kind permission to use material published in our original book, *Mechanized Assembly*, and to Drs. C.R. Poli and L.E. Murch for permission to include much of the material from the *Handbook of Feeding and Orienting Techniques for Small Parts*, which we coauthored.

Finally, thanks go to Dr. P. Dewhurst for his contributions to our work on product design for robot assembly.

Geoffrey Boothroyd

The Author

Geoffrey Boothroyd is Professor Emeritus of Industrial and Manufacturing Engineering at the University of Rhode Island in Kingston. The author or coauthor of more than 100 journal articles, he is also the coauthor or coeditor of several books, including *Fundamentals of Machining and Machine Tools, Second Edition* (with W.A. Knight), *Automatic Assembly* (with C. Poli and L.E. Murch), and *Applied Engineering Mechanics* (with C. Poli) (all titles published by Marcel Dekker.). Additionally, Professor Boothroyd serves as coeditor for the Taylor & Francis series *Manufacturing Engineering and Materials Processing*. A Fellow of the Society of Manufacturing Engineers, he is a member of the National Academy of Engineering, among other professional societies. Professor Boothroyd received Ph.D. (1962) and D.Sc. (1974) degrees in engineering from the University of London, England. His numerous honors and awards include the National Medal of Technology and the SME/ASME Merchant Medal.

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1 Introduction

Since the beginning of the 19th century, the increasing need for finished goods in large quantities, especially in the armaments industries, has led engineers to search for and to develop new methods of manufacture or production. As a result of developments in the various manufacturing processes, it is now possible to mass-produce high-quality durable goods at low cost. One of the more important manufacturing processes is the assembly process that is required when two or more component parts are to be secured together.

The history of assembly process development is closely related to the history of the development of mass-production methods. The pioneers of mass production are also the pioneers of modern assembly techniques. Their ideas and concepts have brought significant improvements in the assembly methods employed in high-volume production.

However, although many aspects of manufacturing engineering, especially the parts fabrication processes, have been revolutionized by the application of automation, the technology of the basic assembly process has failed to keep pace. Table 1.1 shows that, 35 years ago in the U.S., the percentage of the total labor force involved in the assembly process varied from about 20% for the manufacture of farm machinery to almost 60% for the manufacture of telephone and telegraph equipment. Because of this, assembly costs often accounted for more than 50% of the total manufacturing costs.

TABLE 1.1
Percentage of Production Workers Involved in Assembly

Industry	Percentage of Workers Involved in Assembly
Motor vehicles	45.6
Aircraft	25.6
Telephone and telegraph	58.9
Farm machinery	20.1
Household refrigerators and freezers	32.0
Typewriters	35.9
Household cooking equipment	38.1
Motorcycles, bicycles, and parts	26.3

Source: From 1967 Census of Manufacturers, U.S. Bureau of the Census.

Although during the last few decades, efforts have been made to reduce assembly costs by the application of high-speed automation and, more recently, by the use of assembly robots, success has been quite limited. Many workers assembling mechanical products are still using the same basic tools as those employed at the time of the Industrial Revolution.

1.1 HISTORICAL DEVELOPMENT OF THE ASSEMBLY PROCESS

In the early days, the manufacture of the parts and their fitting and assembly were carried out by craftsmen who learned their trade as indentured apprentices. Each part would be tailored to fit its mating parts. Consequently, it was necessary for a craftsman to be an expert in all the various aspects of manufacture and assembly, and training a new craftsman was a long and expensive task. The scale of production was often limited by the availability of trained craftsmen rather than by the demand for the product. This problem was compounded by the reluctance of the craft guilds to increase the number of workers in a particular craft.

The conduct of war, however, requires reliable weapons in large quantities. In 1798, the U.S. needed a large supply of muskets, and federal arsenals could not meet the demand. Because war with the French was imminent, it was not possible to obtain additional supplies from Europe. Eli Whitney, now recognized as one of the pioneers of mass production, offered to contract to make 10,000 muskets in 28 months. Although it took $10^1/_2$ years to complete the contract, Whitney's novel ideas on mass production had been proved successfully. At first, Whitney designed templates for each part, but he could not find machinists capable of following the contours. Next, he developed a milling machine that could follow the templates, but hand-fitting of the parts was still necessary. Eventually, the factory at New Haven, CT, built especially for the manufacture of the muskets, added machines for producing interchangeable parts. These machines reduced the skills required by the various workers and allowed significant increases in the rate of production. In an historic demonstration in 1801, Whitney surprised his distinguished visitors when he assembled a musket lock after selecting a set of parts from a random heap.

The results of Eli Whitney's work brought about three primary developments in manufacturing methods. First, parts were manufactured on machines, resulting in consistently higher quality than that of handmade parts. These parts were interchangeable and, as a consequence, assembly work was simplified. Second, the accuracy of the final product could be maintained at a higher standard. Third, production rates could be significantly increased. These concepts became known as the American system of manufacture.

Oliver Evans' concept of conveying materials from one place to another without manual effort led eventually to further developments in automation for assembly. In 1793, Evans used three types of conveyors in an automatic flour mill that required only two operators. The first operator poured grain into a hopper, and the second filled sacks with the flour produced by the mill. All the intermediate operations were carried out automatically, with conveyors carrying the material from operation to operation.

A significant contribution to the development of assembly methods was made by Elihu Root. In 1849, Root joined the company that was producing Colt six-shooters. Even though, at that time, the various operations of assembling the component parts were quite simple, he divided these operations into basic units that could be completed more quickly and with less chance of error. Root's division of operations gave rise to the concept "divide the work and multiply the output." Using this principle, assembly work was reduced to basic operations and, with only short periods of worker training, high efficiencies could be obtained.

Frederick Winslow Taylor was probably the first person to introduce the methods of time and motion study to manufacturing technology. The object was to save the worker's time and energy by making sure that the work and all things associated with the work were placed in the best positions for carrying out the required tasks. Taylor also discovered that any worker has an optimum speed of working that, if exceeded, results in a reduction in overall performance.

Undoubtedly, the principal contributor to the development of modern production and assembly methods was Henry Ford. He described his principles of assembly in the following words:

> Place the tools and then the men in the sequence of the operations so that each part shall travel the least distance while in the process of finishing.
>
> Use work slides or some other form of carrier so that when a workman completes his operation he drops the part always in the same place which must always be the most convenient place to his hand — and if possible, have gravity carry the part to the next workman.
>
> Use sliding assembly lines by which parts to be assembled are delivered at convenient intervals, spaced to make it easier to work on them.

These principles were gradually applied in the production of the Model T Ford automobile.

The modern assembly-line technique was first employed in the assembly of a flywheel magneto. In the original method, one operator assembled a magneto in 20 min. It was found that when the process was divided into 29 individual operations carried out by different workers situated at assembly stations spaced along an assembly line, the total assembly time was reduced to 13 min 10 sec. When the height of the assembly line was raised by 8 in., the time was reduced to 5 min, which was only one fourth of the time required in the original process of assembly. This result encouraged Henry Ford to utilize his system of assembly in other departments of the factory, which were producing subassemblies for the car. Subsequently, this brought a continuous and rapidly increasing flow of subassemblies to those working on the main car assembly. It was found that these workers could not cope with the increased load, and it soon became clear that the main assembly would also have to be carried out on an assembly line. At first, the movement of the main assemblies was achieved simply by pulling them by a rope from station to station. However, even this development produced an amazing reduction in the total time of assembly from 12 hr 28 min to 5 hr 50 min. Eventually, a power-driven endless conveyor was installed; it was flush with the floor and wide enough to accommodate a chassis. Space was provided for workers either to sit or stand while they carried out their operations, and the conveyor moved at a speed of 6 ft/min past 45 separate workstations. With the introduction of this conveyor, the total assembly time was reduced to 93 min. Further improvements led to an even shorter overall assembly time and, eventually, a production rate of 1 car every 10 sec of the working day was achieved.

Although Ford's target of production had been exceeded and the overall quality of the product had improved considerably, the assembled products sometimes varied from the precise standards of the hand-built prototypes. Eventually, Ford adopted a method of isolating difficulties and correcting them in advance before actual mass production began. The method was basically to set up a pilot plant where a complete assembly line was installed in which were used the same tools, templates, forming devices, gauges, and even the same labor skills that would eventually be used for mass production. This method has now become the standard practice for all large assembly plants.

The type of assembly system described in the preceding text is usually referred to as a *manual assembly line*, and it is still the most common method of assembling mass- or large-batch-produced products. Since the beginning of the 20th century, however, methods of replacing manual assembly workers by mechanical devices have been introduced. These devices take the form of automatic assembly devices or workheads with part-feeding mechanisms and, more recently, robots with part trays.

Thus, in the beginning, automated screwdrivers, nut runners, riveters, spot-welding heads, and pick-and-place mechanisms were positioned on transfer devices that moved the assemblies from station to station. Each workhead was supplied with oriented parts either from a magazine or from an automatic feeding and orienting device, usually a vibratory-bowl feeder. The special single-purpose workheads could continually repeat the same operation, usually taking no more than a few seconds. This meant that completed assemblies were produced at rates on the order of 10–30/min. For two-shift working, this translates into an annual production volume of several million.

Automation of this type was usually referred to as *mechanization* and because it could be applied only in mass production, its development was closely tied to certain industries such as those manufacturing armaments, automobiles, watches and clocks, and other consumer products. Mechanization was used in the manufacture of individual items such as light bulbs and safety pins that are produced in large quantities. However, it was probably in process manufacturing, such as that found in the food, drug, and cosmetic industries, that mechanization was first applied on a large scale.

Estimates of the proportion of mass-produced durable goods to the total production of durable goods range from 15 to 20%. It is not surprising, therefore, that only about 5% of products are automatically assembled, the remainder being assembled manually. As a result, since World War II, increasing attention has been given to the possibility of using robots in assembly work. It was felt that, because robots are basically versatile and reprogrammable, they could be applied in small- and medium-batch manufacturing situations, which form over 80% of all manufacture.

According to Schwartz [1], George Devol, Jr., patented a programmable transfer device in 1954, which served as the basis for the modern industrial robot. The first modern industrial robot, the Unimate [2] was conceived in 1956 at a meeting between inventors George Devol and Joseph Engelberger. In 1961 the Unimate joined the assembly line at General Motors handling die castings.

The first uses of industrial robots were in materials handling such as die-casting and punch-press operations, and by 1968 they started to be used in assembly. By 1972, more than 30 different robots were available from 15 manufacturers.

In spite of these developments, mechanical and electromechanical assemblies remain difficult to automate except in mass-production quantities. The exception to this is the electronics industry, more specifically, the printed-circuit-board (PCB) assembly. Because of the special nature of this product, introduced in the early 1950s, it has been found possible to apply assembly automation even in small-batch production.

At first, PCB components were hand-inserted and their leads hand-soldered. To reduce the soldering time, wave-soldering was developed in which all the leads are soldered in one pass of the board through the soldering machine. The next step was automatic insertion of the component leads. Although initially most small components were axial-lead components, several large electronics manufacturers developed multiple-lead insertion systems. The first company to produce these systems commercially was USM (United Shoe Machinery).

The PCB is an ideal product for the application of assembly automation. It is produced in vast quantities, albeit in a multitude of styles. Assembly of components is carried out in the same direction, and the components types are limited. With the standardization of components now taking place, a high proportion of PCBs can be assembled entirely automatically. Also, the automatic-insertion machines are easy to program and set up and can perform one to two insertions per second. Consequently, relatively slow manual assembly is often economic for only very small batches.

With the present widespread engineering trend toward replacing mechanical control devices and mechanisms with electronics, PCB assembly automation is now finding broad application; indeed, one of the principal applications of assembly robots is the insertion of nonstandard (odd-form) electronic components that cannot be handled by the available automatic-insertion machines.

For many years, manufacturers of electrical and electronic products have spent more on assembly technology than on any other industry [3].

1.2 CHOICE OF ASSEMBLY METHOD

When considering the manufacture of a product, a company must take into account the many factors that affect the choice of assembly method. For a new product, the following considerations are generally important:

1. Suitability of the product design
2. Production rate required
3. Availability of labor
4. Market life of the product

If the product has not been designed with automatic assembly in mind, manual assembly is probably the only possibility. Similarly, automation will not be practical unless the anticipated production rate is high. If labor is plentiful, the degree of automation desirable will depend on the anticipated reduction in the cost of assembly and the increase in production rate, assuming the increase can be absorbed by the market. The capital investment in automatic machinery must usually be amortized over the market life of the product. Clearly, if the market life of the product is short, automation will be difficult to justify.

A shortage of assembly workers will often lead a manufacturer to consider automatic assembly when manual assembly would be less expensive. This situation frequently arises when a rapid increase in demand for a product occurs. Another reason for considering automation in a situation in which manual assembly would be more economical is for research and development purposes, where experience in the application of new equipment and techniques is considered desirable. Many of the early applications of assembly robots were conducted on this basis.

Following are some of the advantages of automation applied in appropriate circumstances:

1. Increased productivity and reduction in costs
2. A more consistent product with higher reliability
3. Removal of operators from hazardous operations
4. The opportunity to reconsider the design of the product

The cost elements for equipment investments that assemblers target change little over the years [3] (Figure 1.1). Direct labor has always been the number one cost that manufacturers hope to reduce by purchasing assembly technology [3].

Productivity is the relationship between the output of goods and services and one or more of the inputs — labor, capital, goods, and natural resources. It is expressed as a ratio of output to input. Both output and input can be measured in different ways, none of them being satisfactory for all purposes. The most

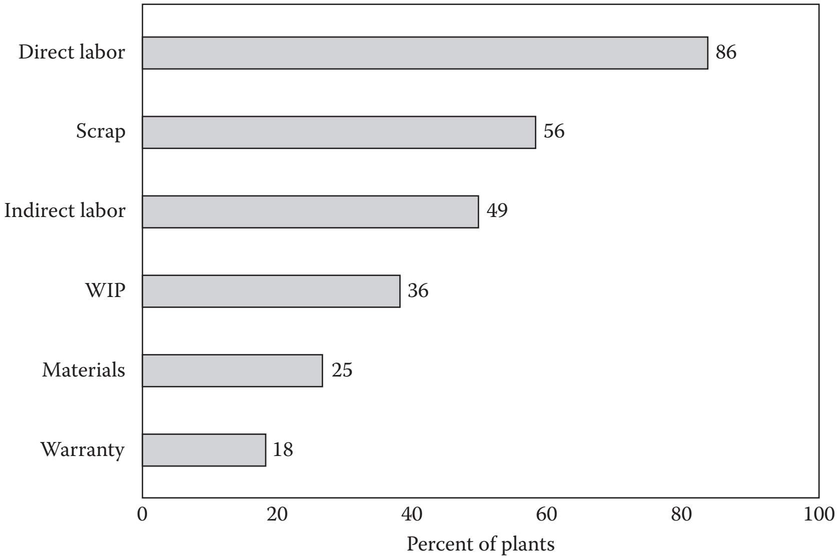


FIGURE 1.1 Cost elements targeted for equipment investments. (From Assembly Survey, *Assembly*, December 2001. With permission.)

common way of defining and measuring productivity is output per man-hour, usually referred to as *labor productivity*. This measure of productivity is easy to understand, and it is the only measure for which reliable data have been accumulated over the years.

However, a more realistic way of defining productivity is the ratio of output to total input, usually referred to as *total productivity*. Total productivity is difficult to measure because it is not generally agreed how the various contributions of labor, machinery, capital, etc., should be weighed relative to each other. Also, it is possible to increase labor productivity while reducing the total productivity. To take a hypothetical example, suppose a company is persuaded to install a machine that costs $200,000 and that it effectively does a job that is the equivalent of one worker. The effect will be to raise the output per man-hour (increase labor productivity) because fewer workers will be needed to maintain the same output of manufactured units. However, because it is unlikely to be economical for a company to spend as much as $200,000 to replace one worker, the capital investment is not worthwhile, and it results in lower total productivity and increased costs. In the long run, however, economic considerations will be taken into account when investment in equipment or labor is made, and improvements in labor productivity will generally be accompanied by corresponding improvements in total productivity.

According to recent surveys, shrinking product life cycles, tighter profit margins, and a slowing economy are forcing manufacturers to pay off capital equipment investments faster than ever before. In 1999, 64% of manufacturers could wait more than a year before seeing a return. In 2001, only 56% could afford to wait that long [3].

Productivity in manufacturing should be considered particularly important because of the relatively high impact that this sector of industry has on the generation of national wealth. In the U.S., manufacturing absorbs over 25% of the nation's workforce and is the most significant single item in the national income accounts, contributing about 30% of the gross national product (GNP). This figure is about nine times the contribution of agriculture and construction and three times that of finance and insurance. In 1974, manufacturing industries accounted for over two thirds of the wealth-producing activities of the U.S. [4]. Within manufacturing in the U.S., the discrete-parts or durable-goods industries clearly form a major target for productivity improvements because these are under direct attack from imports of economically priced high-quality items. These industries manufacture farm, metal-working, electrical machinery and equipment, home electronic and electrical equipment, engines, communications equipment, motor vehicles, aircraft, ships, and photographic equipment. This important group of industries contribute approximately 13% of the GNP, and their output is 46% of that of the manufacturing sectors and 80% of that of the durable-goods manufacturing industries. These industries are highly significant in international trade, their output constituting 80% of total manufacturing exports. However, these industries are not generally the highly efficient, highly automated mass-production units that one is often led to believe they are. The great bulk of the products of these industries are produced in small to medium batches in inefficient factories by using relatively ancient machines and tools. These industries typically depend on manual labor for the handling and assembly of parts, labor provided with tools no more sophisticated than screwdrivers, wrenches, and hammers. It is not surprising, therefore, that, as we have seen, for a wide variety of manufacturing industries, assembly accounts for more than 50% of the total manufacturing cost of a product and more than 40% of the labor force. This means that assembly should be given high priority in the attempts to improve manufacturing productivity.

In the past, in most manufacturing industries, when a new product was considered, careful thought was given to how the product would function, to its appearance, and sometimes to its reliability. However, little thought was given to how easily the product could be assembled and how easily the various parts could be manufactured. This philosophy is often referred to as the "over the wall" approach or "we design it, you make it." In other words, there is an imaginary wall between the design and manufacturing functions; designs are thrown over the wall to manufacturing, as illustrated in Figure 1.2 [5]. This attitude is particularly serious as it affects assembly. The fundamental reason for this is that most manufacturing of component parts is accomplished on machines that perform tasks that cannot be performed manually, whereas machines that can perform even a small fraction of the selection, inspection, and manipulative capabilities of a manual assembly worker are rare. This has resulted in great reliance on the versatility of assembly workers, particularly in the design of a product.

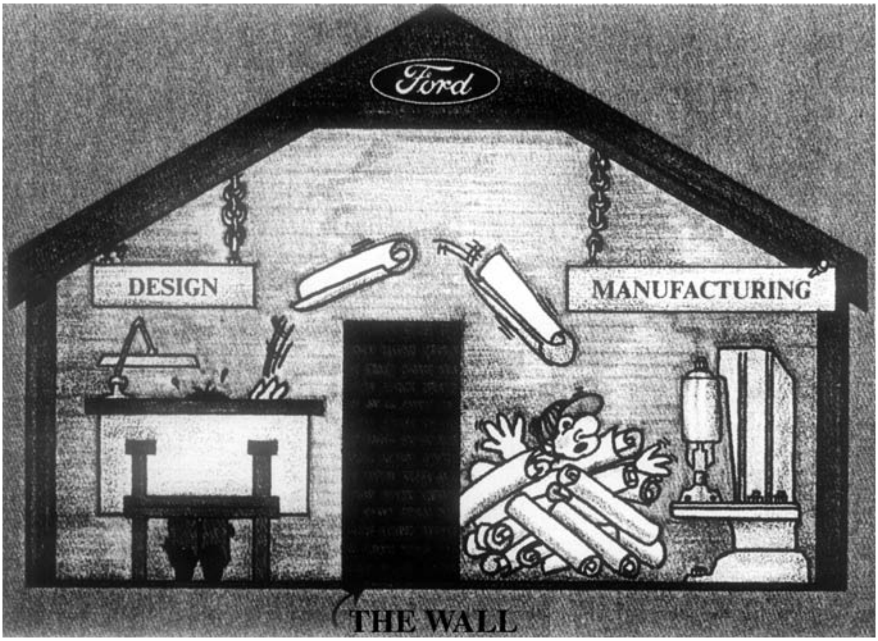


FIGURE 1.2 Illustrating "over the wall" design. (From Munro, S., Illustrating "over the wall" design, private communication.)

For example, an assembly worker can quickly conduct a visual inspection of the part to be assembled and can discard obviously defective parts, whereas elaborate inspection systems would often be required to detect even the most obviously defective part. If an attempt is made to assemble a part that appears to be acceptable but is in fact defective, an assembly worker, after unsuccessfully trying to complete the assembly, can reject the part quickly without a significant loss in production. In automatic assembly, however, the part might cause a stoppage of an automatic workhead or robot, resulting in system downtime while the fault is located and corrected. On the other hand, if a part has only a minor defect, an assembly worker may be able to complete the assembly, but the resulting product may not be satisfactory. It is often suggested that one advantage of automatic assembly is that it ensures a product of consistently high quality because the machine cannot handle parts that do not conform to the required specifications. Another advantage is that automatic assembly forces ease of assembly to be considered in the design of the product.

In some situations, assembly by manual workers would be hazardous because of high temperatures and the presence of toxic or even explosive substances. Under these circumstances, productivity and cost considerations become less important.

1.3 SOCIAL EFFECTS OF AUTOMATION

Much has been said and written regarding the impact of automation and robots in industry. In the 1980s, newspapers and television gave us the impression that all consumer products would soon be assembled by general-purpose robots. Nothing could be further from the truth. Often, publicity such as this led many an industrial manager to inquire why their own company was not using robots in this way and to issue directives to investigate the possibility. An assembly robot was then purchased, and suitable applications sought. This turned out to be surprisingly difficult, and what usually followed was a full-scale development of a robot assembly system so that the various problem areas could be uncovered. The system thus developed was never meant to be economic although that was not always admitted. In fact, assembly systems based on a single general-purpose assembly robot that performs all the necessary assembly operations are difficult to justify on economic grounds. The central reason for this is that the peripheral equipment (feeders, grippers, etc.) needed to build an economic robot assembly station had not yet been developed. The practical difficulties are severe, and so, there is no justification for prophesying mass unemployment as a result of the introduction of assembly robots. Moreover, history has shown that special-purpose one-of-a-kind assembly automation (which is relatively easy although expensive to apply) has not had the kind of impact that was feared 25 years ago. In some limited areas, such as the spot welding of car bodies, industrial robots have made a significant impact. Special-purpose robots (or programmable automatic insertion machines) are now used in over 50% of PCB assembly. However, the application of general-purpose robots in batch assembly is, like all other technological changes, taking place slowly. It should be understood that industrial robots are simply one more tool in the techniques available to manufacturing engineers for improving productivity in manufacturing.

Table 1.2 shows the results of a survey illustrating that as much is spent on parts feeders as on assembly robots. Also, twice as much is spent on single-station assembly systems that probably assemble two or three parts, and five times as much on multistation assembly systems. [3]

Considering the overall picture, the robot is not proving to be a particularly effective tool in assembly. Indeed, much greater improvements in manufacturing productivity can be obtained by carefully considering ease of assembly during the design of the products.

It is appropriate to address more carefully the fear that robots are going to have serious adverse effects on employment in manufacturing. The following quotation is taken from the evidence of a prominent industrialist addressing a U.S. Senate subcommittee on labor and public welfare [6]:

> From a technological point of view, automation is working, but the same cannot be said so confidently from the human point of view. The technologists have done and are doing their job. They have developed and are developing equipment that works

TABLE 1.2
Spending on Assembly Equipment

Equipment Type	Percentage of Total Spending	Estimated Total Dollars Spent ($M)
Automated dispensing	4	85
Multistation assembly systems	26	556
Single-station assembly machines	10	213
Parts feeders	5	107
Conveyors	4	85
Power tools	9	192
Welding, soldering, and brazing	11	235
Robots	5	107
PCB assembly equipment	7	149
Test and inspection	10	213
Wire processing	3	64
Workstations and accessories	5	107
Other	1	21
TOTAL	100	2,134

Source: From Assembly Survey, *Assembly*, December 2001.

> miracles. But as is too often the case in this age of the widening gap between scientific progress and man's ability to cope with it, we have failed to keep pace.
>
> Much of this failure is due, I think, to the existence of a number of myths about automation …. The most seductive of these is the claim that, for a number of reasons, automation is not going to eliminate many jobs …. Personally, I think … that automation is a major factor in eliminating jobs in the United States, at the rate of more than 40,000 per week, as previous estimates have put it.

These observations are quoted from Senate hearings in 1963 — over 40 years ago! Even before that, in 1950, a famous Massachusetts Institute of Technology professor of mathematics, Norbert Wiener, stated:

> Let us remember that the automatic machine … is the precise economic equivalent of slave labor. Any labor which competes with slave labor must accept the economic conditions of slave labor. It is perfectly clear that this will produce an unemployment situation, in comparison with which … the depression of the thirties will seem a pleasant joke.

In retrospect, it is amusing to look back at the serious predictions made by famous and influential individuals and see just how wrong they were. However, the problem is that equally famous people have been making similar pronouncements about the automatic factory, which was considered to be just around the corner 20 years ago and is still just around the corner! It is worth examining these alarmist views a little more carefully because of the very real and adverse effects they can have on public opinion. These views are generally based on two false premises:

1. That the introduction of improved techniques for the manufacture of goods produces rapid and significant changes in productivity
2. That improvements in productivity have an overall negative effect on employment

History shows that the introduction of improved manufacturing techniques takes place very slowly. With specific reference to assembly robots, an MIT professor puts it as follows [7]:

> There has been in recent years a great deal of publicity associated with robotics. The implication has been that great progress is being made in implementing robot technology to perform assembly tasks. In fact, progress during the last ten years has been slow and steady. Present perception in the popular press is that robots are about to take over many manufacturing tasks. Yet, there is a growing awareness that this is not so. The rate of progress in this area is accelerating as more money and more interest are being directed toward the problems.
>
> The automated factory of the future is still many years away, and steps in that direction are being taken at a pace which will allow us, if we so choose, to study and make enlightened decisions about the effects of implementation of flexible automation on unemployment, quality and structure of the work environment, and quality of the workpiece produced.

Even though this statement is reasonable and considered, there is an implication in the last sentence that automation will have the effect of increasing unemployment. Regarding this common premise, it has long been established [8] that there is little, if any, correlation between productivity changes and changes in employment. Employment problems in the U.S. auto industry, for example, have mostly arisen from the lack of manufacturing productivity improvement rather than the opposite. Certainly there is no evidence that manufacturing process innovation is, on balance, adverse to employment.

In summarizing a study of technology and employment, Cyert and Mowery [9] stated:

> (i) Historically, technological change and productivity growth have been associated with expanding rather than contracting total employment and rising earnings. The future will see little change in this pattern. As in the past, however, there will be declines in specific industries and growth in others, and some individuals will be displaced. Technological changes in the U.S. economy is not the sole or even the most important cause of these dislocations.

> (ii) The adoption of new technologies generally is gradual rather than sudden. The employment impacts of new technologies are realized through the diffusion and adoption of technology, which typically take a considerable amount of time. The employment impacts of new technologies therefore are likely to be felt more gradually than the employment impacts of other factors, such as changes in exchange rates. The gradual pace of technological change should simplify somewhat the development and implementation of adjustment policies to help affected workers.
>
> (iii) Within today's international economic environment, slow adoption by U.S. firms (relative to other industrial nations) of productivity-increasing technologies is likely to cause more job displacement than the rapid adoption of such technologies. Much of the job displacement since 1980 does not reflect a sudden increase in the adoption of labor saving innovations but instead is due in part to increased U.S. imports and sluggish exports, which in turn reflect macroeconomic forces (the large U.S. budget deficit), slow adoption of some technologies in U.S. manufacturing, and other factors.
>
> (iv) Technology transfer increasingly incorporates significant research findings and innovations. In many technologies, the U.S. no longer commands a significant lead over industrial competitor nations. Moreover, the time it takes another country to become competitive with U.S. industry or for U.S. firms to absorb foreign technologies has become shorter.

In conclusion, it can be said that justification for the use of assembly automation equipment can be made on economic grounds (which is quite difficult to do) or because the supply of local manual labor becomes inadequate to meet the demand. In the past, the latter has most often been the real justification, without completely disregarding the first, of course. Thus, the real social impact of the use of robots in assembly is unlikely to be of major proportions.

Turning to the effects of product design, it can be stated that improvements in product design leading to greater economy in the manufacture of parts and the assembly of products will always result in improvements in both labor and total productivity. To design a product for ease of assembly requires no expenditure on capital equipment, and yet the significant reductions in assembly times have a marked effect on productivity.

In fact, the design of products for ease of assembly has much greater potential for reducing costs and improving productivity than assembly automation [10]. This is illustrated by the example shown in Figure 1.3. This graph shows clearly that automation becomes less attractive as the product design is improved. For the original design manufactured in large volumes, high-speed assembly automation would give an 86% reduction in assembly costs and, for medium production volumes, robot assembly would give a 61% reduction. However, with the most efficient design consisting of only two parts, design for assembly (DFA) gives a 92% reduction in manual assembly costs and, for this design, the further benefits obtained through automation are negligible.

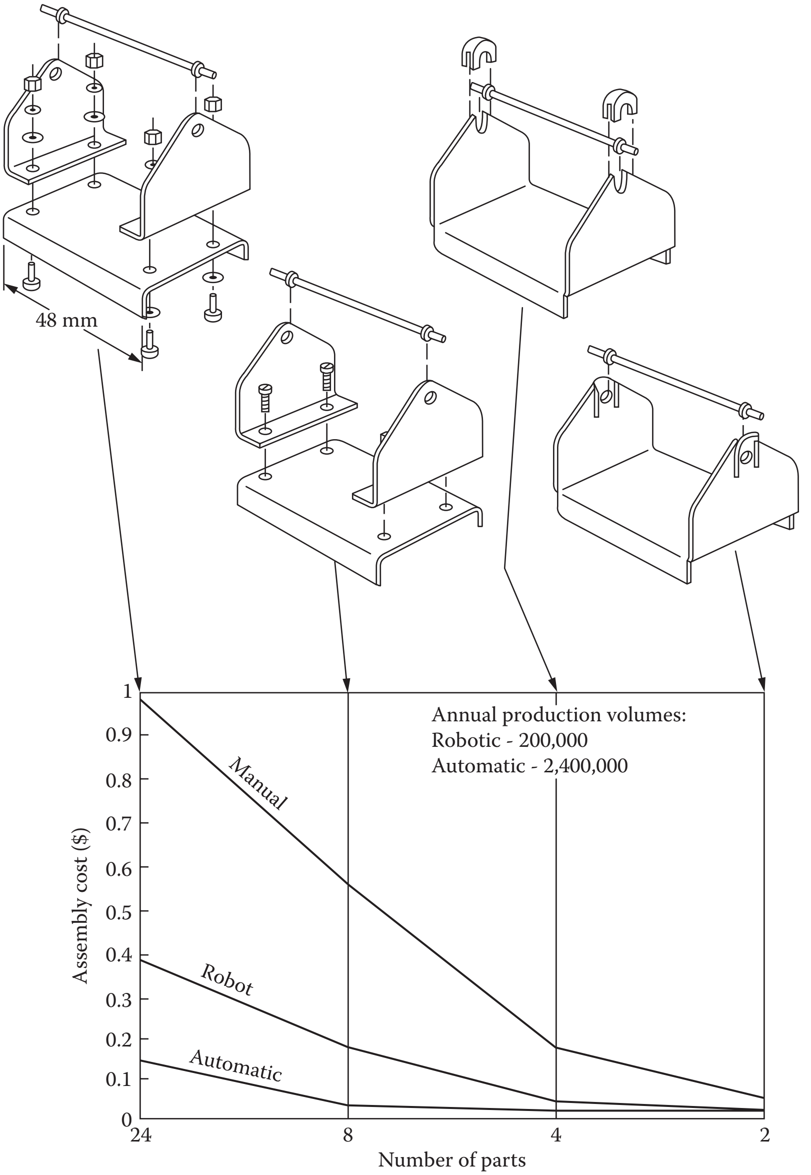


FIGURE 1.3 Example of the effect of automation and design for assembly. (From Boothroyd, G., Design for assembly — the key to design for manufacture, *International Journal of Advanced Manufacturing Technology*, Vol. 2, No. 3, 1987.)

This example reveals a kind of paradox created when designing a product for ease of automatic assembly. In many cases the product becomes so easy to assemble manually that this would become the most economic method of assembly. A practical example of this is the IBM Proprinter, which was introduced as an accessory to the PC. This printer was designed to be assembled using robots and, indeed, the design of the product was carried out in parallel with the design of the factory that would assemble them. When the IBM Proprinter was introduced, the ease of its assembly was demonstrated by manually assembling it in only 3 min. This was to be compared with the estimated assembly time of 30 min for the Japanese Epson printer, the previous dot matrix printer used as an accessory to the PC. However, as the robotic factory had already been built, this was the way the printer was assembled, whereas hindsight would indicate that manual assembly was probably the more economic approach. Indeed, it is understood that, eventually, this was the way the printer was assembled.

In the following chapters, the basic components of assembly machines are presented, and the overall performance of assembly systems is discussed. Finally, detailed analyses of the suitability of parts and products for both manual and automatic assembly are presented.

REFERENCES

1. Schwartz, W.H., An Assembly Hall of Fame, *Assembly Engineering*, January 1988.
2. Nof, S.Y. (Ed.), *Handbook of Industrial Robots, 2nd ed.*, John Wiley & Sons, New York, 1999.
3. Assembly Survey, *Assembly*, December 2001.
4. The National Role and Importance of Manufacturing Engineering and Advanced Manufacturing Technology, position paper of the S.M.E. (Society of Manufacturing Engineers), May 8, 1978.
5. Munro, S., Illustrating “over the wall” design, private communication.
6. Terborgh, G., *The Automation Hysteria*, Norton, New York, 1965.
7. Seering, W.P. and Gordon, S.J., Review of Literature on Automated Assembly, Department of Mechanical Engineering, MIT, Cambridge, MA, November 1983
8. Aron, P., The Robot Scene in Japan: An Update, Report No. 26, Diawan Securities American, Inc., New York, 1983.
9. Cyert, R.M. and Mowery, D.C., *Technology and Employment*, National Academy Press, Washington, D.C., 1987.
10. Boothroyd, G., Design for Assembly — The Key to Design for Manufacture, *International Journal of Advanced Manufacturing Technology*, Vol. 2, No. 3, 1987.

2 Automatic Assembly Transfer Systems

In automatic assembly, the various individual assembly operations are generally carried out at separate workstations. For this method of assembly, a machine is required for transferring the partly completed assemblies from workstation to workstation, and a means must be provided to ensure that no relative motion exists between the assembly and the workhead or robot while the operation is being carried out. As the assembly passes from station to station, it is necessary that it be maintained in the required attitude. For this purpose, the assembly is usually built up on a base or work carrier, and the machine is designed to transfer the work carrier from station to station; an example of a typical work carrier is shown in Figure 2.1. Assembly machines are usually classified according to the system adopted for transferring the work carriers (Figure 2.2). Thus, an in-line assembly machine is one in which the work carriers are transferred in line along a straight slideway, and a rotary machine is one in which the work carriers move in a circular path. In both types of machine, the transfer of work carriers may be continuous or intermittent.

2.1 CONTINUOUS TRANSFER

With continuous transfer, the work carriers are moving at a constant speed while the workheads keep pace. When the operations are completed, the workheads return to their original positions and, again, keep pace with the work carriers. Alternatively, the workheads move in a circular path tangential to the motion of the work carriers. In either case, the assembly operations are carried out during the period in which the workheads are keeping pace with the work carriers.

Continuous-transfer systems have limited application in automatic assembly because the workheads and associated equipment are often heavy and must therefore remain stationary. It is also difficult to maintain sufficiently accurate alignment between the workheads and work carriers during the operation cycle because both are moving. Continuous-transfer machines are most common in industries such as food processing or cosmetics, where bottles and jars have to be filled with liquids.

2.2 INTERMITTENT TRANSFER

Intermittent transfer is the system more commonly employed for automatic assembly. As the name implies, the work carriers are transferred intermittently, and the workheads remain stationary. Often, the transfer of all the work carriers

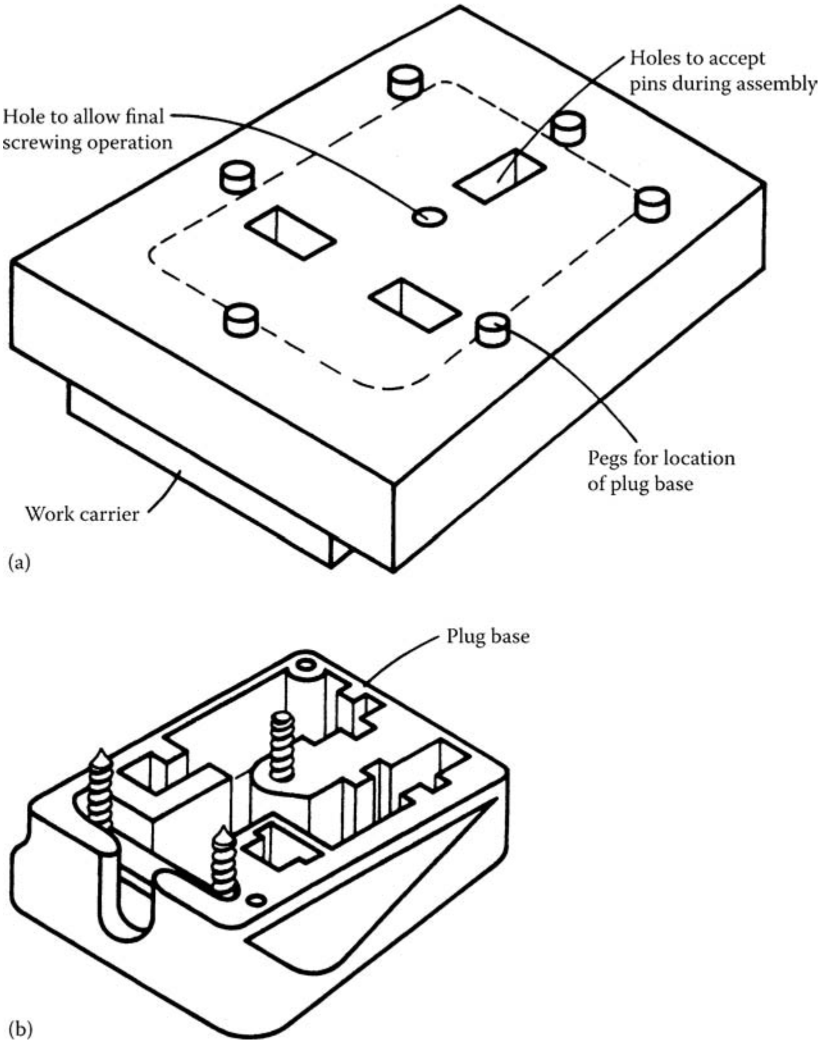

Holes to accept pins during assembly
Hole to allow final screwing operation
Pegs for location of plug base
Work carrier
(a)
Plug base
(b)

FIGURE 2.1 Work carrier suitable for holding and transferring three-pin power plug base.

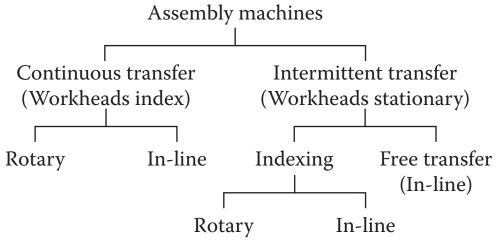

Assembly machines
Continuous transfer (Workheads index)
Intermittent transfer (Workheads stationary)
Rotary
In-line
Indexing
Free transfer (In-line)
Rotary
In-line

FIGURE 2.2 Basic types of assembly machines.

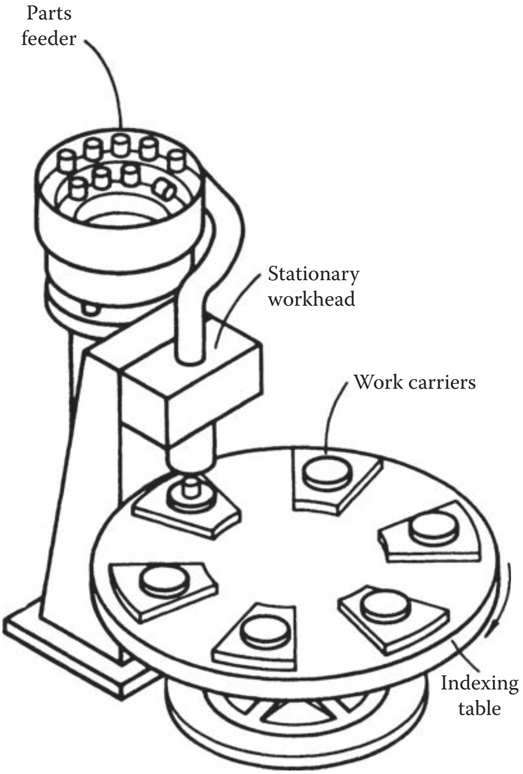


FIGURE 2.3 Rotary indexing machine (with one workhead shown).

occurs simultaneously, and the carriers then remain stationary to allow time for the assembly operations. These machines may be termed *indexing machines*, and typical examples of the rotary and in-line types of indexing machines are shown in Figure 2.3 and Figure 2.4, respectively. With rotary indexing machines, indexing of the table brings the work carriers under the various workheads in turn, and assembly of the product is completed during one revolution of the table. Thus, at the appropriate station, a completed product may be taken off the machine after each index. The in-line indexing machine works on a similar principle but, in this case, a completed product is removed from the end of the line after each index. With in-line machines, provision must be made for returning the empty work carriers to the beginning of the line. The transfer mechanism on in-line machines is generally one of two types: the shunting work carrier or the belt-driven work carrier.

The shunting work carrier transfer system is shown in Figure 2.5. In this system, the work carriers have lengths equal to the distance moved during one index. Positions are available for work carriers at the beginning and end of the assembly line, where no assembly takes place. At the start of the cycle of operations, the work carrier position at the end of the line is vacant. A mechanism

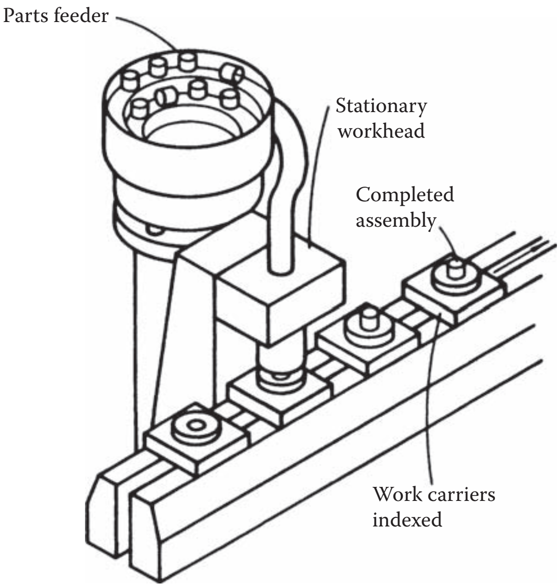


FIGURE 2.4 In-line indexing machine (with one workhead shown).

pushes the line of work carriers up to a stop at the end of the line, and this indexes the work carriers' position. The piston then withdraws, and the completed assembly at the end of the line is removed. The empty work carrier from a previous cycle that has been delivered by the return conveyor is raised into position at the beginning of the assembly line.

Although the system described here operates in the vertical plane, the return of work carriers can also be accomplished in the horizontal plane. In this case, transfer from the assembly line to the return conveyor (and vice versa) is simpler, but greater floor area is used. In practice, when operating in the horizontal plane, it is more usual to dispense with the rapid return conveyor and to fit further assembly heads and associated transfer equipment in its place (Figure 2.6). However, this system has the disadvantage that access to the various workheads may be difficult.

A further disadvantage with all shunting work carrier systems is that the work carriers themselves must be accurately manufactured. For example, if an error of 0.025 mm were to occur on the length of each work carrier in a 20-station machine, an error in alignment of 0.50 mm would occur at the last station. This error could create serious difficulties in the operation of the workheads. However, in all in-line transfer machines, it is usual for each work carrier, after transfer, to be finally positioned and locked by a locating plunger before the assembly operation is initiated.

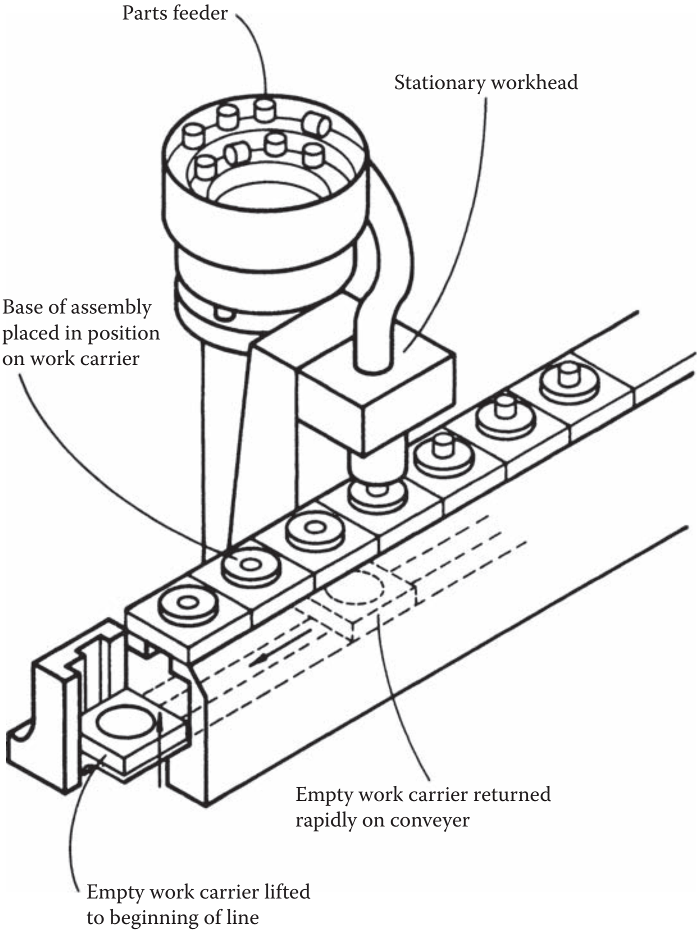

Parts feeder
Stationary workhead
Base of assembly placed in position on work carrier
Empty work carrier returned rapidly on conveyer
Empty work carrier lifted to beginning of line

FIGURE 2.5 In-line transfer machine with shunting work carriers returned in vertical plane.

The belt-driven work-carrier transfer system is illustrated in Figure 2.7. Basically, this machine uses an indexing mechanism that drives a belt or flexible steel band to which the work carriers are attached. The work carriers are spaced to correspond to the distance between the workheads.

Instead of attaching the work carriers rigidly to the belt, it is possible to employ a chain that has attachments to push the work carriers along guides. In this case, the chain index can be arranged to leave the work carriers short of their final position, allowing location plungers to bring them into line with the workheads.

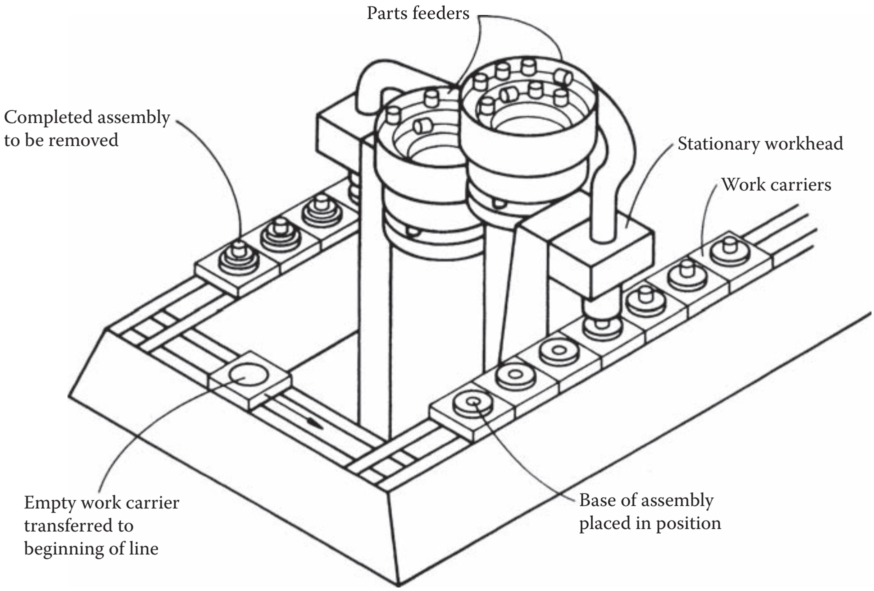

Parts feeders
Completed assembly to be removed
Stationary workhead
Work carriers
Empty work carrier transferred to beginning of line
Base of assembly placed in position

FIGURE 2.6 In-line transfer machine with shunting work carriers returned in horizontal plane.

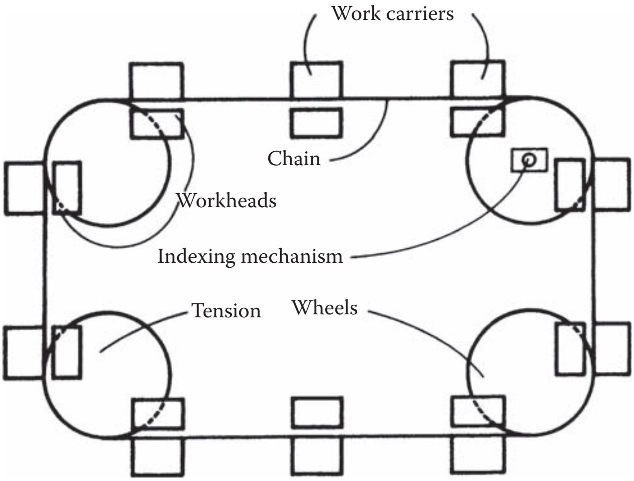


FIGURE 2.7 Belt-driven transfer system.

2.3 INDEXING MECHANISMS

Huby [1] lists the factors affecting the choice of indexing mechanism for an assembly machine as follows:

1. The required life of the machine
2. The dynamic torque capacity required
3. The static torque capacity
4. The power source required to drive the mechanism
5. The acceleration pattern required
6. The accuracy of positioning required from the indexing unit

Generally, an increase in the size of a mechanism increases its life. Experience shows which mechanisms usually have the longest life for given applications; this is discussed later.

The dynamic torque capacity is the torque that must be supplied by the indexing unit during the index of a fully loaded machine. The dynamic torque capacity is found by adding the effects of inertia and friction and multiplying by the life factor of the unit, the latter factor being derived from experience with the use of the indexing unit.

The static torque capacity is the sum of the torques produced at the unit by the operation of the workheads. If individual location plungers are employed at each workhead, these plungers are usually designed to withstand the forces applied by the workheads; in such a case, the static torque capacity required from the indexing unit will probably be negligible. The power required to drive an indexing unit is obtained from the dynamic torque applied to the unit during the machine index.

The form of the acceleration curve for the indexing unit may be very important when there is any possibility that a partially completed assembly may be disturbed during the machine index. A smooth acceleration curve will also reduce the peak dynamic torque and will thus assist the driving motor in maintaining a reasonably constant speed during indexing, thereby increasing the life of the machine. The accuracy of the indexing required will not be great if locating plungers are employed to perform the final positioning of the work carriers or indexing table.

Various indexing mechanisms are available for use on automatic assembly machines; typical examples are given in Figure 2.8 to Figure 2.10. These mechanisms fall into two principal categories: those that convert intermittent translational motion (usually provided by a piston) into angular motion by means of a rack and pinion or ratchet and pawl (Figure 2.8), and those that are continuously driven, such as the Geneva mechanism (Figure 2.9) or the crossover or scroll cam shown in Figure 2.10.

For all but very low-speed or very small indexing tables, the rack-and-pinion or ratchet-and-pawl mechanisms are unsuitable because they have a tendency to overshoot. The acceleration properties of both these systems are governed entirely

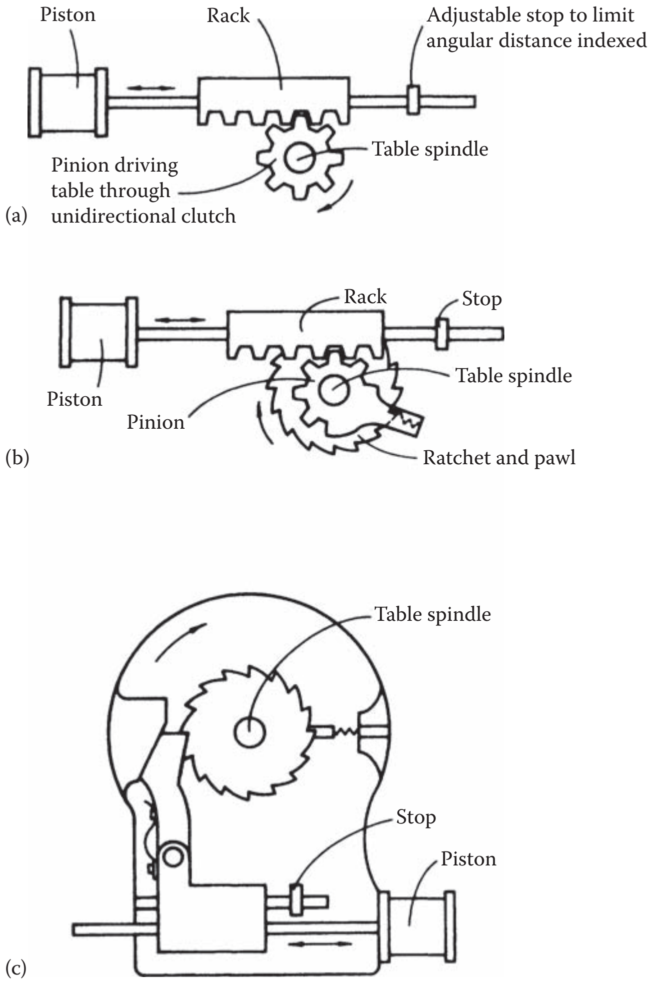


FIGURE 2.8 Indexing mechanisms: (a) rack and pinion with unidirectional clutch; (b) rack and pinion with ratchet and pawl; (c) ratchet and pawl.

by the acceleration pattern of the linear power source. To ensure a fairly constant indexing time, if the power source is a pneumatic cylinder, it is usual to underload the cylinder, in which case the accelerations at the beginning and end of the stroke are very high and produce undesirable shocks. The ratchet-and-pawl mechanism requires a takeup movement and must be fairly robust if it is to have a long life. The weakest point in the mechanism is usually the pawl pin and, if this is not well lubricated, the pawl will stick and indexing will not occur.

The Geneva-type indexing mechanism has more general applications in assembly machines, but its cost is higher than the mechanisms described earlier. It is capable of transmitting a high torque relative to its size and has a smooth

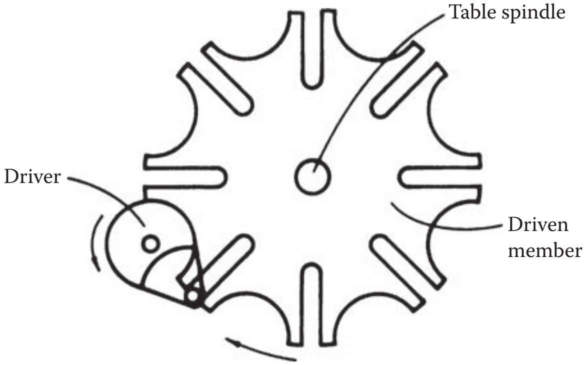


FIGURE 2.9 Geneva mechanism.

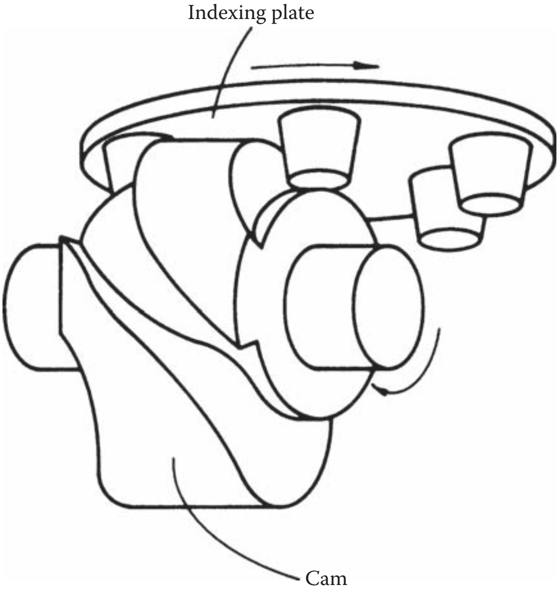


FIGURE 2.10 Crossover cam indexing unit.

acceleration curve. However, it has a high peak dynamic torque immediately before and after the reversal from positive to negative acceleration. In its basic form, the Geneva mechanism has a fairly short life, but wear can be compensated for by adjustment of the centers. The weakest point in the mechanism is the indexing pin, but breakages of this part can be averted by careful design and avoidance of undue shock reactions from the assembly machine. A characteristic of the Geneva mechanism is its restriction on the number of stops per revolution.

This is primarily due to the accelerations that occur with three-stop and more than eight-stop mechanisms.

In a Geneva mechanism, the smaller the number of stops, the greater the adverse mechanical advantage between the driver and the driven members. This results in a high indexing velocity at the center of the indexing movement and gives a very peaked acceleration graph. On a three-stop Geneva, this peaking becomes very pronounced and, because the mechanical advantage is very high at the center of the movement, the torque applied to the index plate is greatly reduced when it is most required. The solution to these problems results in very large mechanisms relative to the output torque produced.

As the number of stops provided by a Geneva mechanism increases, the initial and final accelerations during indexing increase although the peak torque is reduced. This is due to the increased difficulty in placing the driver center close to the tangent of the indexing slot on the driven member.

For a unit running in an oil bath, the clearance between the driver and driven members during the locking movement is approximately 0.025 mm. To allow for wear in this region, it is usual to provide a small center-distance adjustment between the two members. The clearance established after adjustment is the main factor governing the indexing accuracy of the unit, and this will generally become less accurate as the number of stops is increased. Because of the limitations in accuracy, it is usual to employ a Geneva mechanism in conjunction with a location plunger; in this way, a relatively cheap and accurate method of indexing is obtained.

The crossover cam type of indexing mechanism shown in Figure 2.10 is capable of transmitting a high torque, has a good acceleration characteristic, and is probably the most consistent and accurate form of indexing mechanism. Its cost is higher than that of the alternative mechanisms described earlier, and it also has the minor disadvantage of being rather bulky. The acceleration characteristics are not fixed as with other types of indexing mechanisms, but a crossover cam can be designed to give almost any required form of acceleration curve. The normal type of cam is designed to provide a modified trapezoidal form of acceleration curve, resulting in a low peak dynamic torque and fairly low mean torque. The cam can be designed to give a wide range of stops per revolution of the index plate, and the indexing is inherently accurate. A further advantage is that it always has at least two indexing pins in contact with the cam.

Figure 2.11 shows the acceleration patterns of the modified trapezoidal, sine, and modified sine cams and the Geneva mechanism for the complete index of a four-stop unit. It can be seen that the modified trapezoidal form gives the best pattern for the smoothest operation and lowest peaking. The sine and modified sine both give smooth acceleration, but the peak torque is increased, whereas with the Geneva mechanism, the slight initial shock loading and the peaking at the reversal of the acceleration are clearly evident.

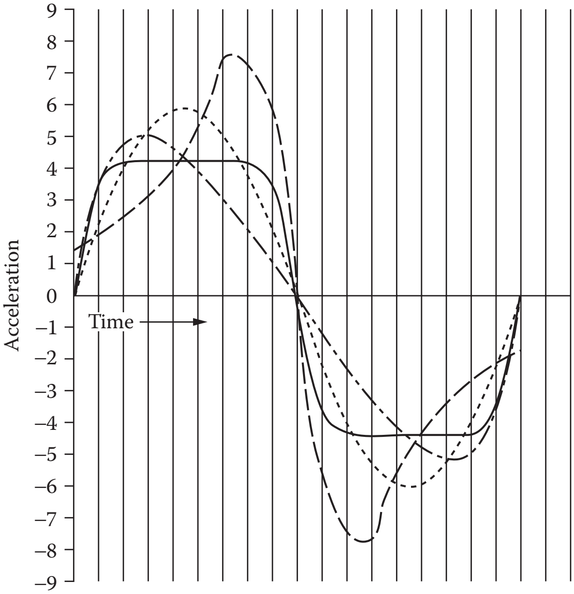


FIGURE 2.11 Comparison of acceleration curves for a Geneva mechanism and various designs of crossover cams: modified trapezoidal, — ; four-stop Geneva, – – ; modified sine, – - – - ; sine, ----. (Adapted from Huby, E., Assembly Machine Transfer Systems, paper presented at the Conference on Mechanized Assembly, July 1966, Royal College of Advanced Technology, Salford, England. With permission.)

2.4 OPERATOR-PACED FREE-TRANSFER MACHINE

With all the transfer systems described earlier, it is usual for the cycle of operations to occur at a fixed rate, and any manual operations involved must keep pace; this is referred to as *machine pacing*. Machines are available, however, for which a new cycle of operations can be initiated only when signals indicating that all the previous operations have been completed are received. This is referred to as *operator pacing*.

One basic characteristic common to all the systems described is that a breakdown of any individual workhead will stop the whole machine, and production will cease until the fault has been rectified. One type of in-line intermittent operator-paced machine, known as a *free-transfer or nonsynchronous machine* (Figure 2.12), does not have this limitation. In this design, the spacing of the workstations is such that buffer stocks of assemblies can accumulate between adjacent stations. Each workhead or operator works independently, and the assembly process is initiated by the arrival of a work carrier at the station. The first operation is to lift the work carrier clear of the conveyor and clamp it in position. After the assembly operation has been completed, the work carrier is released and transferred to the next station by the conveyor, provided that a vacant space

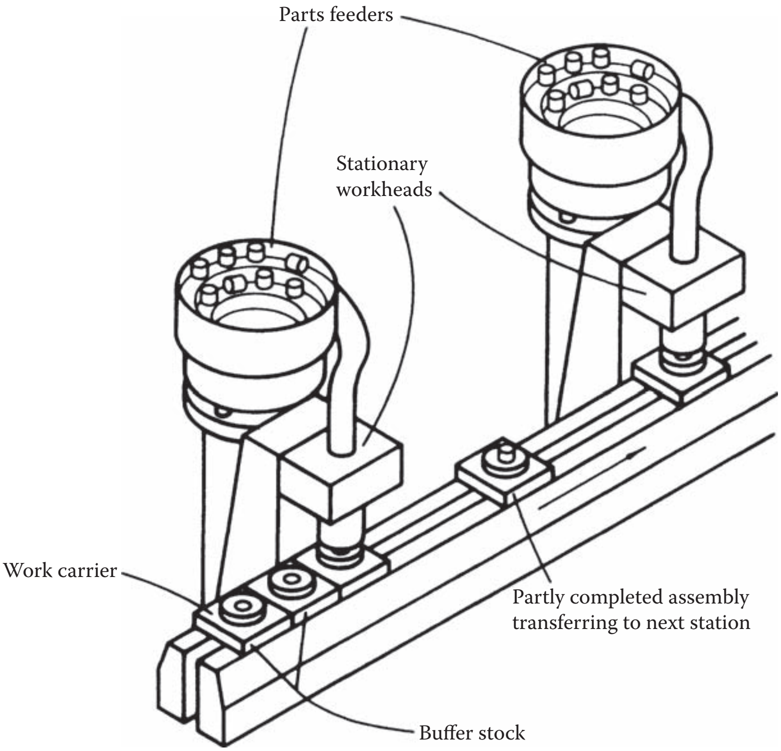


FIGURE 2.12 In-line free-transfer or nonsynchronous machine.

is available. Thus, on a free-transfer machine, a fault at any one station will not necessarily prevent the other stations from working. It will be seen later that this can be an important factor when considering the economics of various transfer machines for automatic assembly.

REFERENCES

1. Huby, E., Assembly Machine Transfer Systems, paper presented at the Conference on Mechanized Assembly, July 1966, Royal College of Advanced Technology, Salford, England.

3 Automatic Feeding and Orienting — Vibratory Feeders

The vibratory-bowl feeder is the most versatile of all hopper feeding devices for small engineering parts. In this feeder (Figure. 3.1), the track along which the parts travel is helical and passes around the inside wall of a shallow cylindrical hopper or bowl. The bowl is usually supported on three or four sets of inclined leaf springs secured to a heavy base. Vibration is applied to the bowl from an electromagnet mounted on the base, and the support system constrains the movement of the bowl so that it has a torsional vibration about its vertical axis, coupled with a linear vertical vibration. The motion is such that any small portion of the inclined track vibrates along a short, approximately straight path, which is inclined to the horizontal at an angle greater than that of the track. When component parts are placed in the bowl, the effect of the vibratory motion is to cause them to climb up the track to the outlet at the top of the bowl. Before considering the characteristics of vibratory-bowl feeders, it is necessary to examine the mechanics of vibratory conveying. For this purpose, it is convenient to deal with the motion of a part on a straight vibrating track that is inclined at a small angle to the horizontal.

3.1 MECHANICS OF VIBRATORY CONVEYING

In the following analysis, the track of a vibratory feeder is assumed to move bodily with simple harmonic motion along a straight path inclined at an angle $(\theta + \psi)$ to the horizontal, as shown in Figure 3.2. The angle of inclination of the track is θ, and ψ is the angle between the track and its line of vibration. The frequency of vibration f (usually 60 Hz, in practice) is conveniently expressed in this analysis as $\omega = 2\pi f$ rad/sec where ω is the angular frequency of vibration. The amplitude of vibration a_0 and the instantaneous velocity and acceleration of the track may all be resolved in directions parallel and normal to the track. These components will be referred to as *parallel and normal motions* and will be indicated by the subscripts p and n, respectively. It is assumed in the analysis that the motion of a part of mass m_p is independent of its shape and that air resistance is negligible. It is also assumed that there is no tendency for the part to roll down the track.

It is useful to consider the behavior of a part that is placed on a track whose amplitude of vibration is increased gradually from zero. For small amplitudes,

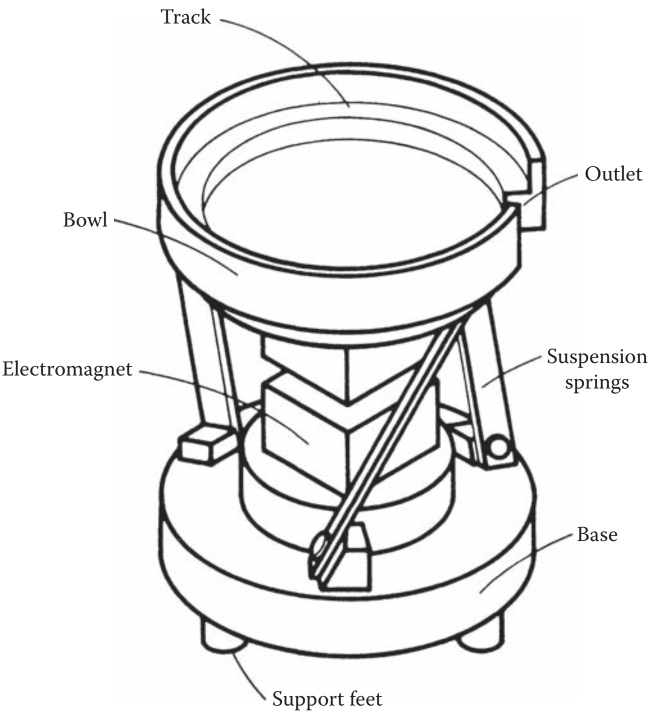


FIGURE 3.1 Vibratory-bowl feeder.

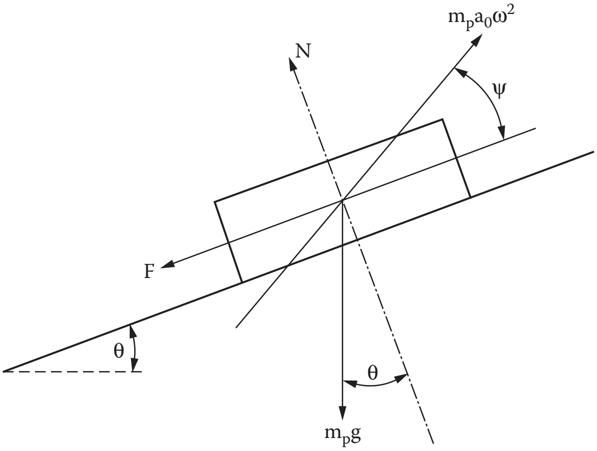


FIGURE 3.2 Force acting on a part in vibratory feeding.

the part will remain stationary on the track because the parallel inertia force acting on the part will be too small to overcome the frictional resistance F between the part and the track. Figure 3.2 shows the maximum inertia force acting on the part when the track is at the upper limit of its motion. This force has parallel and normal components of $m_p a_0\,\omega^2 \cos\psi$ and $m_p a_0\,\omega^2 \sin\psi$, respectively, and it can be seen that, for sliding up the track to occur,

$$m_p a_0\,\omega^2 \cos\psi > m_p g \sin\theta + F \tag{3.1}$$

where

$$F = \mu_s N = \mu_s [m_p g \cos\theta - m_p a_0 \omega^2 \sin\psi] \tag{3.2}$$

and where μ_s is the coefficient of static friction between the part and the track. The condition for forward sliding up the track to occur is, therefore, given by combining Equation 3.1 and Equation 3.2. Thus,

$$\frac{a_0\omega^2}{g} > \frac{\mu_s \cos\theta + \sin\theta}{\cos\psi + \mu_s \sin\psi} \tag{3.3}$$

Similarly, it can be shown that, for backward sliding to occur during the vibration cycle,

$$\frac{a_0\omega^2}{g} > \frac{\mu_s \cos\theta - \sin\theta}{\cos\psi - \mu_s \sin\psi} \tag{3.4}$$

The operating conditions of a vibratory conveyor may be expressed in terms of the dimensionless normal track acceleration A_n/g_n, where A_n is the normal track acceleration ($A_n = a_n\omega^2 = a_0\omega^2 \sin\psi$), g_n the normal acceleration due to gravity ($g \cos\theta$), and g the acceleration due to gravity (9.81 m/sec^2). Thus,

$$\frac{A_n}{g_n} = \frac{a_0\omega^2 \sin\psi}{g\cos\theta} \tag{3.5}$$

Substitution of Equation 3.5 in Equation 3.3 and Equation 3.4 gives, for forward sliding,

$$\frac{A_n}{g_n} > \frac{\mu_s + \tan\theta}{\cot\psi + \mu_s} \tag{3.6}$$

and for backward sliding,

$$\frac{A_n}{g_n} > \frac{\mu_s - \tan\theta}{\cot\psi - \mu_s} \tag{3.7}$$

For values of $\mu_s = 0.8$, $\theta = 3°$ (0.05 rad) and $\psi = 30°$ (0.52 rad), Equation 3.6 and Equation 3.7 show that the ratio A_n/g_n must be greater than 0.34 for forward sliding to occur and greater than 0.8 for backward sliding. With these conditions, it is clear that, for all amplitudes of vibration giving a value of A_n/g_n greater than 0.34, forward sliding will predominate and the part will climb the track, sliding forward or both forward and backward during each vibration cycle.

The limiting condition for forward conveying to occur is given by comparing Equation 3.6 and Equation 3.7. Thus, for forward conveying,

$$\tan\psi > \frac{\tan\theta}{\mu_s^2}$$

or, when θ is small,

$$\tan\psi > \frac{\theta}{\mu_s^2} \tag{3.8}$$

For values of $\mu_s = 0.8$ and $\theta = 3°$ (0.05), ψ must be greater than 4.7° (0.08 rad) for forward conveying to occur.

With sufficiently large vibration amplitudes, the part will leave the track and "hop" forward during each cycle. This can occur only when the normal reaction N between the part and the track becomes zero. From Figure 3.2,

$$N = m_p g \cos\theta - m_p a_0 \omega^2 \sin\psi \tag{3.9}$$

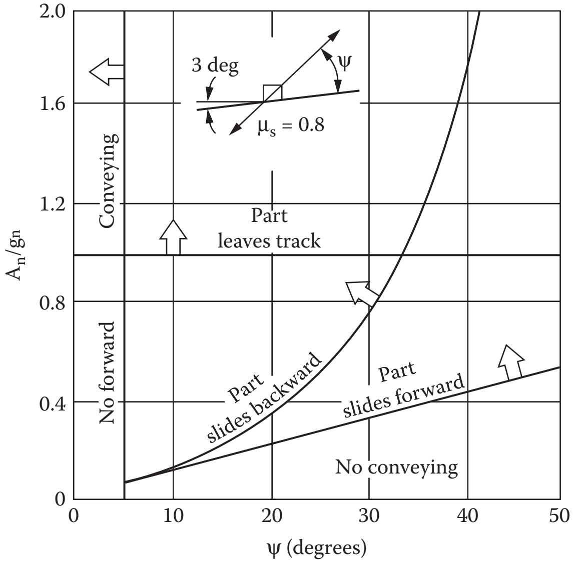
and, therefore, for the part to leave the track,

$$\frac{a_0\omega^2}{g} > \frac{\cos\theta}{\sin\psi}$$

or

$$\frac{A_n}{g_n} > 1.0 \tag{3.10}$$

It is clear from the earlier examples, however, that the part slides forward before it leaves the track during each cycle. Figure 3.3 graphically illustrates these equations, showing the effect of the vibration angle ψ on the limiting values



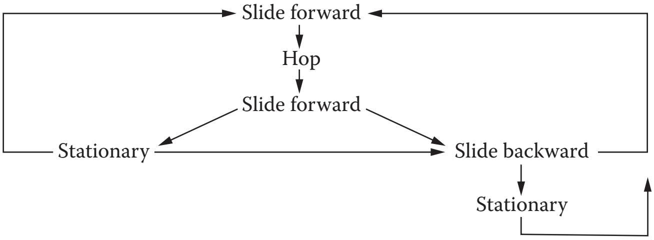


FIGURE 3.3 Limiting conditions for various modes of vibratory conveying. A_n is the normal track acceleration and g_n the normal gravitational acceleration.

of the dimensionless normal acceleration A_n/g_n for forward sliding to occur, for both forward and backward sliding to occur, and for the part to hop along the track.

The detailed types of motion that may occur in vibratory feeding have been described in the literature [1]. For all conditions, the part starts to slide forward at some instant when the track is nearing the upper limit of its motion. When there is no hopping mode, this forward sliding continues until the track is nearing the lower limit of its motion, at which point the part may remain stationary relative to the track or slide backward until the cycle is complete. In some cases, the stationary period is followed by a period of backward sliding only or of backward sliding followed by yet another stationary period. Finally, the forward sliding is followed by a period of backward sliding and then a stationary period to complete the cycle.

Analysis and experiment have shown that higher feed rates are obtained with the hopping mode of conveying (that is, when $A_n/g_n > 1.0$). The modes of conveying are summarized in the following flow diagram:

Clearly, a complete analysis of all the possible modes of vibratory conveying is complicated. Such an analysis has been made [1] and leads to equations that must be solved numerically. For the purposes of the present discussion, it is considered adequate to describe only the main results of this analysis and the results of some experimental tests. In the following, the effects of frequency f, track acceleration A_n/g_n, track angle θ vibration angle ψ, and the effective coefficient of friction μ on the mean conveying velocity v_m are discussed separately.

3.2 EFFECT OF FREQUENCY

One principal result of the theoretical work is that, for given conditions and for constant track acceleration (that is, when A_n/g_n is constant), the mean conveying velocity v_m is inversely proportional to the vibration frequency f. Hence,

$$fv_m = \text{constant} \tag{3.11}$$

This is illustrated in Figure 3.4, where the effect of track acceleration on the mean conveying velocity is plotted for three values of the vibration angle ψ. It can be seen that the experimental values for a range of frequencies fall on one line when the factor fv_m is used as a measure of the conveying velocity. This confirms the prediction of the theoretical analysis. One consequence of this result is that, for high conveying velocities and hence high feed rates, it is desirable to use as low a frequency as is practicable. However, because the track accelerations must be kept constant, this result means that there is a corresponding increase in track amplitude. The mechanical problems of connecting the feeder to a stationary machine imposes a lower limit on the frequency, but some advantages can be gained by lowering the operating frequency of a bowl feeder from the usual 60 Hz to 30 Hz [1].

3.3 EFFECT OF TRACK ACCELERATION

Figure 3.4 shows that an increase in track acceleration A_n/g_n generally produces an increase in conveying velocity. At some point, however, although theoretical analysis predicts further increases in velocity, increases in A_n/g_n cease to have a significant effect. This finding may be explained as follows: If the track acceleration is increased until $A_n/g_n > 1.0$, the part starts to hop once during each cycle, as described earlier. At first, the velocity of impact as the part lands on the track is small but, as the track acceleration is increased further, the impact velocity also increases until, at some critical value, the part starts to bounce. Under these circumstances, the feeding cycle becomes erratic and unstable, and the theoretical predictions are no longer valid.

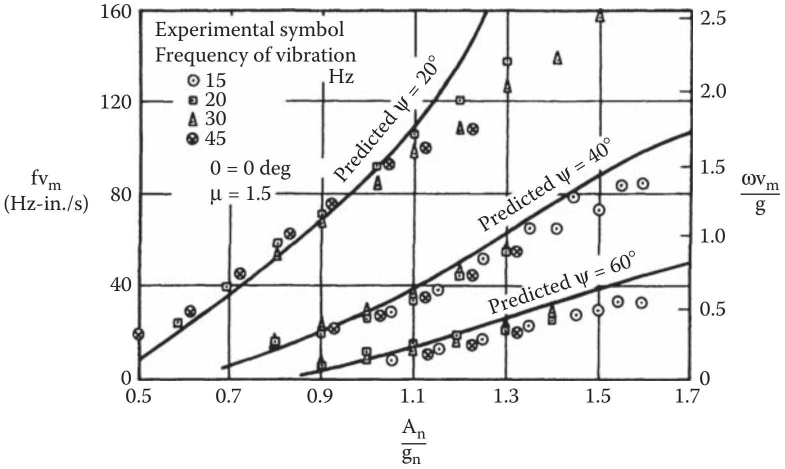


FIGURE 3.4 Effect of vibration angle, track acceleration, and frequency on conveying velocity, where ψ is the vibration angle (deg), *f* the frequency (Hz), θ the track angle (deg), μ the coefficient of friction, and v_m the mean conveying velocity. (From Redford, A.H. and Boothroyd, G., Vibratory Feeding, *Proceedings of the Institution of Mechanical Engineers*, Vol. 182, Part 1, No. 6, p. 135, London, 1967–1968. With permission.)

To obtain the most efficient feeding conditions, it is necessary to operate with values of A_n/g_n greater than unity but below the values that will produce unstable conditions. From Figure 3.4, it can be seen that, within this range, an approximately linear relationship exists between the factors fv_m and A_n/g_n for each value of ψ, for given values of track angle θ and coefficient of friction μ.

3.4 EFFECT OF VIBRATION ANGLE

From Figure 3.4, it can be seen that the conveying velocity is sensitive to changes in the vibration angle ψ. The effect is shown more clearly in Figure 3.5, which indicates that an optimum vibration angle exists for any given condition. For clarity, these theoretical predictions are shown without the supporting experimental evidence. Previous work has revealed the relationship between the optimum vibration angle ψ_{opt} and the coefficient of friction, as shown in Figure 3.6, for a practical value of track acceleration, where A_n/g_n is 1.2.

3.5 EFFECT OF TRACK ANGLE

Figure 3.7 gives the effect of the track angle θ on the conveying velocity for various track accelerations when μ is 0.2. These results show that the highest velocities are always achieved when the track angle is zero and that forward

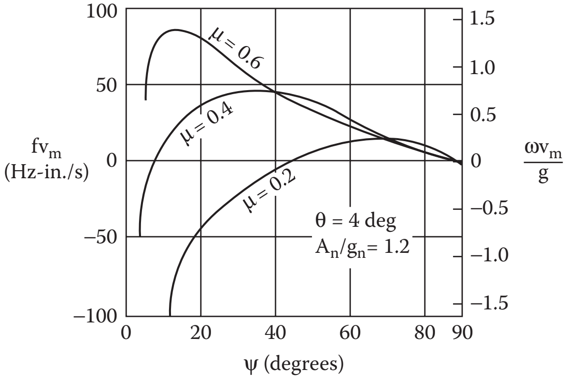


FIGURE 3.5 Theoretical results showing the effect of vibration angle on the mean conveying velocity. (From Redford, A.H. and Boothroyd, G., Vibratory Feeding, *Proceedings of the Institution of Mechanical Engineers*, Vol. 182, Part 1, No. 6, p. 135, London, 1967–1968. With permission.)

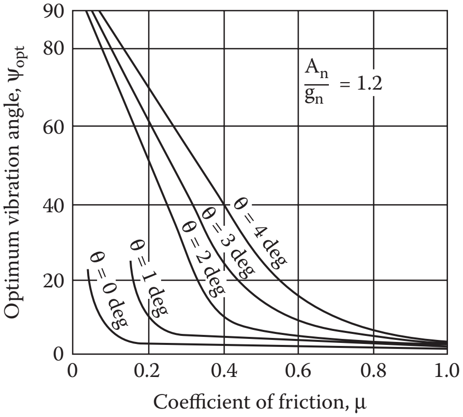


FIGURE 3.6 Theoretical results showing the effect of coefficient of friction on the optimum vibration angle. (From Redford, A.H. and Boothroyd, G., Vibratory Feeding, *Proceedings of the Institution of Mechanical Engineers*, Vol. 182, Part 1, No. 6, p. 135, London, 1967–1968. With permission.)

conveying is achieved only with small track angles. The mechanical design of a bowl feeder necessitates a positive track angle of 3–4° in order to raise the parts to the bowl outlet. However, it can be seen from the figure that even if conveying can be achieved on the track, the mean conveying velocity will be significantly lower than that around the flat bottom of the bowl. This means that, in practice, the parts on the track will invariably be pushed along by those at the bottom of the bowl, where they tend to circulate at a greater speed. This leads to certain

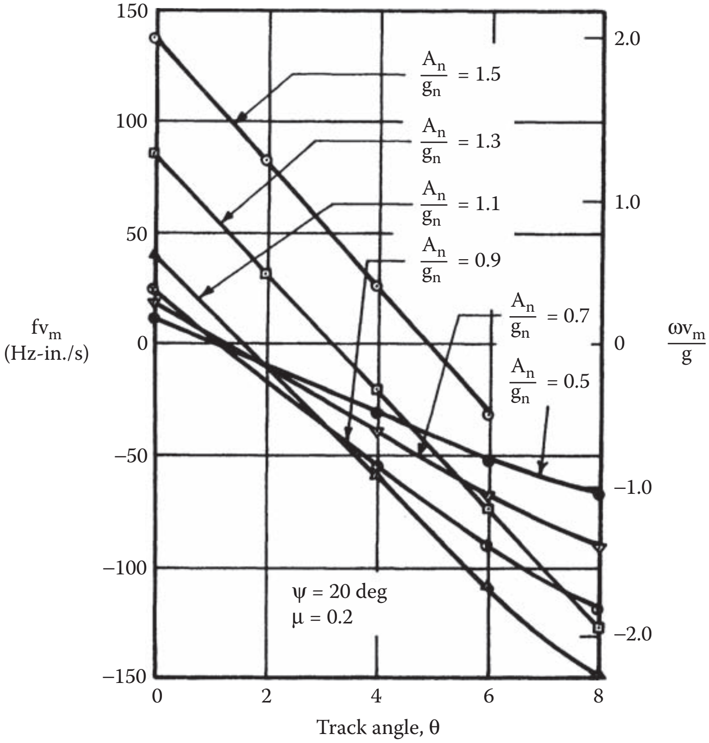


FIGURE 3.7 Theoretical results showing the effect of track angle on the conveying velocity. (From Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966. With permission.)

problems in the design of orienting devices, which are generally placed around the upper part of the bowl track. During the testing of such orienting devices, parts transported individually along the track may behave correctly. However, when the bowl is filled and a line of parts forms along the track, the parts tend to be forced through the orienting devices by the pressure of those at the bottom of the bowl. This pressure may often lead to jamming and a general unreliability in operation.

From the foregoing discussion, it is clear that, considering the unrestricted feed rate from a bowl feeder, a track angle of 0° should be employed because the feeding characteristics in the flat bowl bottom will generally govern the overall performance of the feeder.

3.6 EFFECT OF COEFFICIENT OF FRICTION

The practical range of the coefficient of friction in vibratory feeding is 0.2–0.8. The value 0.2 represents the value for a steel part conveyed on a steel track. When

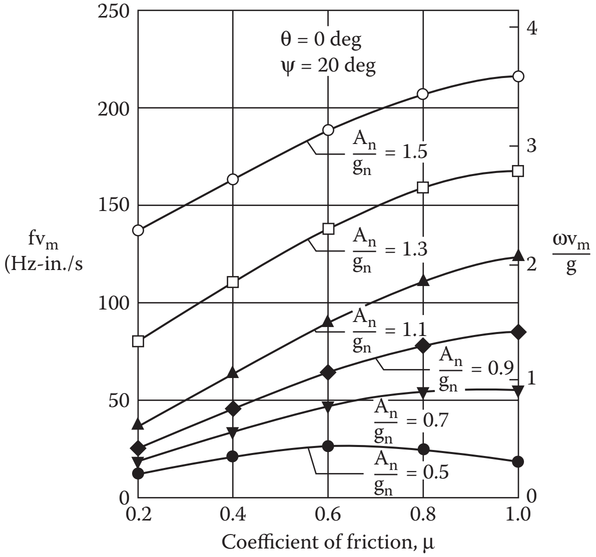


FIGURE 3.8 Theoretical results showing the effect of the coefficient of friction on the conveying velocity. (From Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966. With permission.)

the track is lined with rubber, a common practice in industry, the coefficient of friction may be raised to approximately 0.8.

Figure 3.8 shows the effect of the coefficient of friction on the conveying velocity for a horizontal track, a vibration angle of 20°, and for various track accelerations. It can be seen that, for practical values of track acceleration, an increase in friction leads to an increase in conveying velocity; hence, the advantage provided by coating the tracks of bowl feeders with rubber. Coatings can also reduce the noise level resulting from the motion of the parts, which is often an important consideration.

3.7 ESTIMATING THE MEAN CONVEYING VELOCITY

At any point on a horizontal track, the ratio of the amplitudes of the vertical and horizontal components of vibration is equal to the tangent of the vibration angle ψ. When the bowl is operating properly with no rocking motion, the vertical component of motion a_n will be the same at every location in the bowl. The magnitude of the horizontal component a_p, however, changes with the radial position.

The horizontal component increases linearly with increasing radial position. If the vibration angle ψ_1 at radial position r_1 is known, the vibration angle ψ_2 at a radial position r_2 is found from

$$\tan\psi_2 = \frac{r_1}{r_2}\tan\psi_1 \tag{3.12}$$

If the leaf springs are inclined at 60° (1.05 rad) from the horizontal plane and attached to the bowl 100 mm from the bowl center, the vibration angle at this radius is the complement of the spring inclination angle, or 30° (0.52 rad) if the vibration of the base is neglected. If the vibration of the base is important, the vibration angle should be determined experimentally by comparing the signals from two accelerometers, one mounted vertically and the other horizontally.

For the present example, the magnitude of the vibration angle at a radial position 150 mm from the bowl center can be found from Equation 3.12 and

$$\psi_2 = \arctan\left[\frac{100}{150}\tan 30^\circ\right] = 21^\circ\,(0.37\text{ rad}) \tag{3.13}$$

The vibratory motion of a bowl feeder causes parts randomly deposited at the bottom of the bowl to climb the helical track on the interior of the bowl wall. The conveying velocity of the parts on the inclined track is usually governed by the pushing action of the parts circulating around the bottom of the bowl. For those parts moving on the horizontal bottom of the bowl, the conveying velocity v_m depends mainly on the vibration angle ψ, the amplitude of vibration a_0, and the frequency of vibration f or the angular frequency of vibration ω, where ω equals $2\pi f$. A simple dimensional analysis of this situation shows that

$$\frac{v_m\omega}{g} = \text{function}\left(\frac{a_0\omega^2\sin\psi}{g}, \psi\right) \tag{3.14}$$

where g is the acceleration due to gravity and is equal to 9.81 m/sec^2. The functional relationship from Equation 3.14 is presented graphically in Figure 3.9. For the usual case of a 60-Hz vibration, the conveying velocity is also shown as a function of the vibration angle ψ and the vertical amplitude of vibration, that is, the amplitude normal to the horizontal track. The dimensionless scales shown at the top and at the right of Figure 3.9 can be used for any vibration frequency, including 60 Hz, but this requires additional computation.

For example, suppose that in a 60-Hz vibratory-bowl feeder, the start of the track at the bottom of the bowl is located 150 mm from the bowl center and the vibration angle at this point is 21° (0.37 rad). Then, according to Figure 3.9, the conveying velocity v_m is approximately 36 mm/sec when a_n is 80 μm. As a comparison, if a_n or $a_0 \sin\psi$ equals 80 μm, the magnitude of the dimensionless amplitude is given by

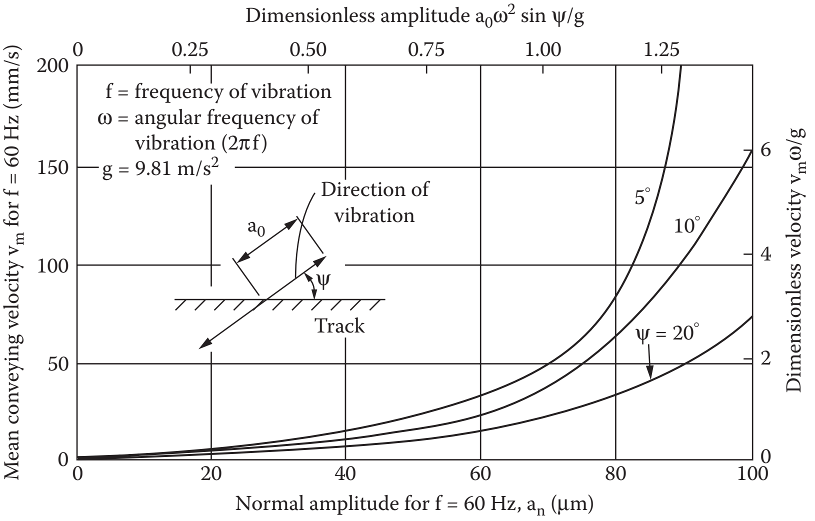


FIGURE 3.9 Estimation of the mean conveying velocity on a horizontal track. (From Boothroyd, G., Poli, C.R., and Murch, L.E., Feeding and Orienting Techniques for Small Parts, SME Technical Paper AD72–763, 1975. With permission.)

$$\frac{a_0\omega^2 \sin\psi}{g} = \frac{(80\times 10^{-6})(2\pi\times 60)^2}{9.81} = 1.16 \tag{3.15}$$

From Figure 3.9, if ψ equals 21° (0.37 rad), the dimensionless velocity $v_m\omega/g$ equals 1.35 and v_m equals 35 mm/sec. The corresponding value of the horizontal amplitude a_p is 210 μm.

The vibration amplitude can be adjusted while an operator monitors a special decal mounted on the outer rim of the bowl. This decal is used to measure the peak-to-peak amplitude or twice the horizontal amplitude of the vibration at that point. The correct value of this horizontal amplitude depends on the bowl diameter and is found from geometry.

Using the previous example, if the diameter of the bowl is 600 mm, the parallel amplitude at the rim is

$$\frac{300}{150}(210) = 421\ \mu\text{m} \tag{3.16}$$

so that the peak-to-peak setting is 0.84 mm. As a consequence, the vibration angle for the last horizontal section of the track is

$$\arctan\left[\frac{80}{420}\right] = 11^\circ\ (0.19\ \text{rad}) \tag{3.17}$$

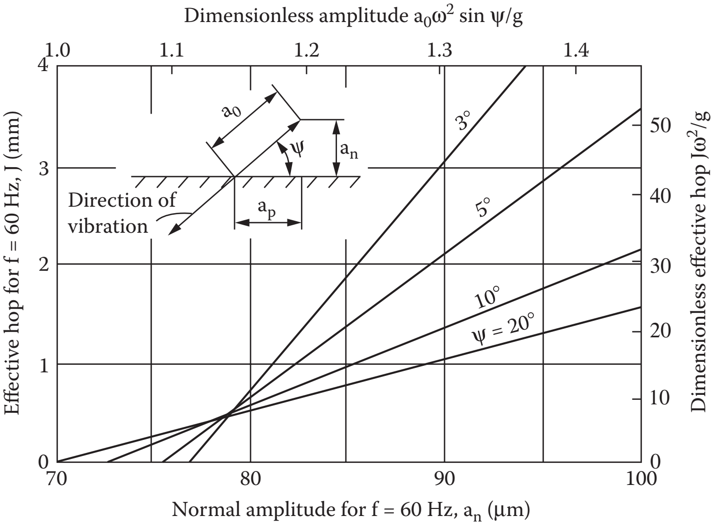


FIGURE 3.10 Theoretical estimate of the length of the effective hop on a horizontal track. (From Boothroyd, G., Poli, C.R., and Murch, L.E., Feeding and Orienting Techniques for Small Parts, SME Technical Paper AD72–763, 1975. With permission.)

As the parts leave the bowl, their conveying velocity is now 70 mm/sec, from Figure 3.9.

Although parts are apparently conveyed by vibratory motion with an almost constant conveying velocity, this motion is, actually, a combination of a variety of dissimilar smaller motions giving the total effect of smooth movement. This combination of smaller motions is cyclic and usually repeats with the frequency of the drive. Some of the details of this motion are important in the design of orienting devices used in vibratory-bowl feeders. Figure 3.10 and Figure 3.11 show the effective length J and height H of a hop for a point mass traveling on a horizontal track as shown in Figure 3.12. The effective length of the hop is the smallest gap in the track that will reject all point masses traveling with this motion.

The magnitude of this effective hop can be determined from Figure 3.10. If the normal amplitude a_n is 80 μm for a 60-Hz vibration and the vibration angle ψ is 11° (0.19 rad), then the value of the effective hop J is 0.6 mm. The scales on the top and right side of Figure 3.10 can be used for other frequencies of vibration, as explained in the discussion of Figure 3.9.

Similarly, Figure 3.11 can be used to determine the magnitude of the maximum height H of the hop above the horizontal track. Using the previous conditions (a_n = 80 μm and vibration frequency of 60 Hz), H is found to be 8 μm.

It should be noted that intensive theoretical and experimental work has been carried out by Jimbo et al. [4] on the mechanics of vibratory feeding and they have presented numerous graphs that can be used to estimate the conveying velocity of a part under a wide range of conditions.

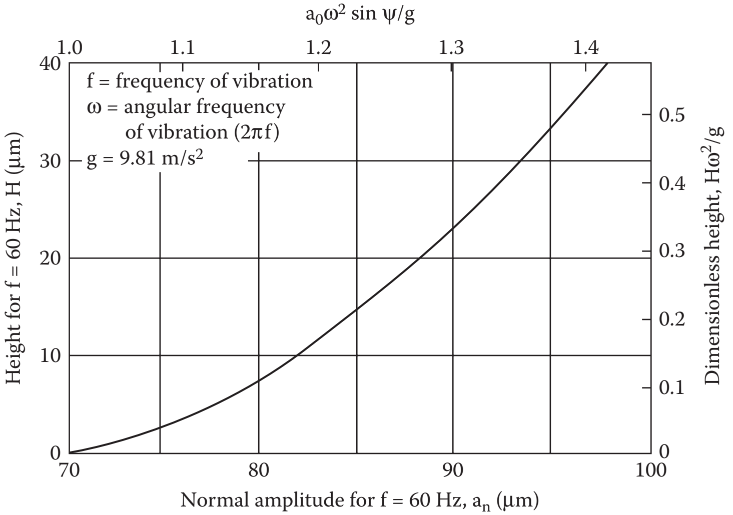


FIGURE 3.11 Theoretical estimate of the maximum height reached by a hopping part above a horizontal track. (From Boothroyd, G., Poli, C.R., and Murch, L.E., Feeding and Orienting Techniques for Small Parts, SME Technical Paper AD72–763, 1975. With permission.)

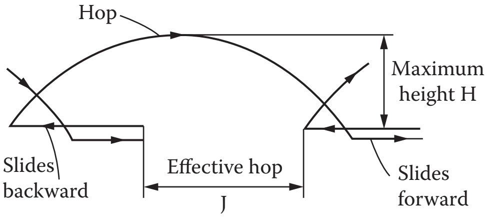


FIGURE 3.12 Typical part motion, including the hop.

3.8 LOAD SENSITIVITY

One of the main disadvantages of vibratory-bowl feeders is the change in their performance as the bowl gradually empties. This change occurs because, for a constant power input, the amplitude of vibration and, hence, the maximum bowl acceleration usually increases as the effective mass of the loaded bowl reduces. It can be deduced from Figure 3.13 that this increase in bowl acceleration will generally result in an increase in the unrestricted feed rate. Vibratory-bowl feeders are often used to convey and orient parts for automatic assembly and, because the workheads on an assembly machine are designed to work at a fixed cycle time, the parts can only leave the feeder at a uniform rate. The feeder must

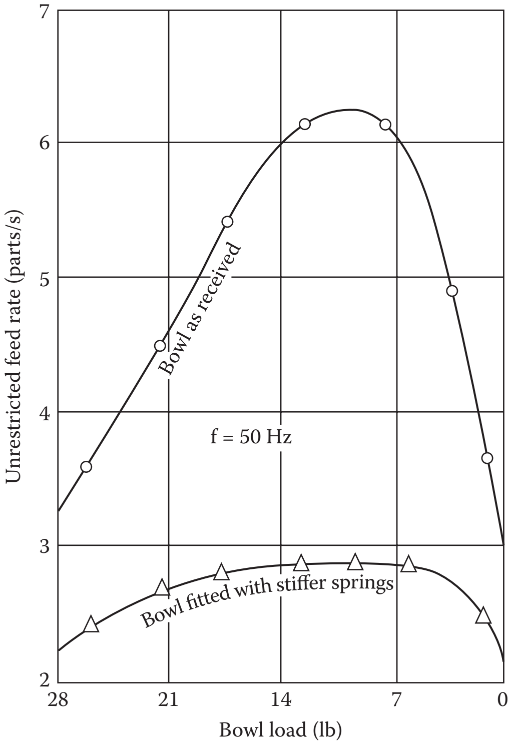


FIGURE 3.13 Experimentally determined load sensitivity of a commercial bowl feeder. (From Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966. With permission.)

therefore be adjusted to overfeed slightly under all conditions of loading, the excess parts being continuously returned from the track to the bottom of the bowl.

The change in performance as a feeder gradually empties is referred to as its *load sensitivity*, and the upper curve in Figure 3.13 shows how the unrestricted feed rate for a commercial bowl feeder in the as-received condition varied as the bowl emptied. It can be seen that the maximum feed rate occurred when the bowl was approximately 25% full and that this represented an increase of approximately 100% over the feed rate obtained with the bowl full. It is of interest to compare this result with the measured changes in bowl acceleration shown in Figure 3.14, where it can be seen that the bowl acceleration and, hence, the amplitude increased continuously until the bowl became empty. Clearly, when a feeder empties, the feed rate will reduce to zero, but Figure 3.13 shows that the feed rate begins to reduce much sooner than might be expected from Figure 3.14. This behavior is considered to be due to the greater velocity of parts in the flat bowl bottom than that on the track; this was described earlier. When the bowl is full, the feed rate depends mainly on the feeding characteristics at the bottom of the bowl, where the general circulation of the parts pushes those on the track.

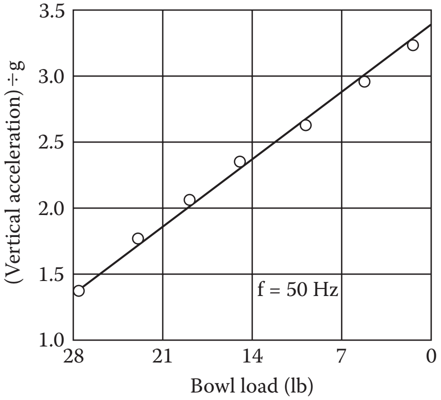


FIGURE 3.14 Effect of bowl load on bowl acceleration. (From Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966. With permission.)

However, as the bowl empties, leaving mainly those parts that remain on the track, the pushing action ceases, and the feed rate depends only on the conveying velocity on the inclined track, which is generally lower than that on a horizontal surface. This explains the difference in character between the graphs in Figure 3.13 and Figure 3.14.

Figure 3.13 suggests that, under the test conditions, the as-received bowl feeder could be used to feed a workhead operating at a maximum rate of 3 insertions per second and that, in this case, there would be considerable recirculation of parts resulting from overfeeding. Assuming that the feeder is to be refilled when it is only 25% full, the feeding characteristics between refills may be reasonably represented by a feed rate increasing linearly as the bowl empties.

3.9 SOLUTIONS TO LOAD SENSITIVITY

One of the simplest solutions to load sensitivity, and the one most commonly used, is the load detector switch together with a secondary feeder. The load detector switch is simply a mechanical arm and limit switch that detects when the level of parts in the bottom of the bowl falls below some predetermined level. When closed, the switch activates the secondary feeder and refills the bowl to a predetermined level. This action essentially increases the frequency of refills, reducing the recirculation effect to almost zero.

A second solution requires modification to the feeder. Frequency-response curves for the vibratory-bowl feeder used in the previous experiments are presented in Figure 3.15. These curves show the effect of changes in the forcing frequency on the bowl acceleration for a constant power input and for various bowl loadings. In these tests, the power input is less than that employed in the test shown in Figure 3.14, but they show the same effect where, for a forcing frequency of 50 Hz, the maximum bowl acceleration is sensitive to changes in

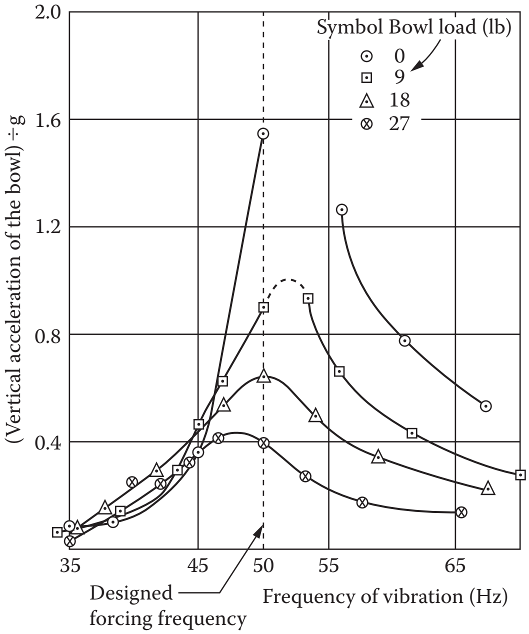


FIGURE 3.15 Frequency-response curves for a vibratory-bowl feeder, showing the effect of bowl load. (From Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966. With permission.)

bowl loading. However, it can also be seen that, whereas for a forcing frequency of 50 Hz (the frequency used in Great Britain), the maximum bowl acceleration is sensitive to changes in bowl loading, for a forcing frequency of approximately 44 Hz, the bowl acceleration is approximately constant for all bowl loadings. Under these latter conditions, the load sensitivity would be considerably reduced. Alternatively, it is clear that increasing the spring stiffness of the bowl supports sufficiently would have the effect of shifting the response curves to the right and minimizing the changes in bowl acceleration for a forcing frequency of 50 Hz. The natural frequency of the empty, as-received bowl was approximately 53 Hz, and tests showed that, if this was increased to 61 Hz by increasing the support spring stiffness, the load sensitivity of the feeder was considerably reduced. The lower curve in Figure 3.13 shows this effect. It can also be seen, however, that the feed rates have been reduced by stiffening the support springs and, therefore, in order to maintain the higher feed rate, a more powerful drive would be required. Generally, vibratory-bowl feeders are tuned to a natural frequency only slightly higher than the frequency of the drive; this serves to minimize the power by utilizing the ease of transmission of vibration at or near the natural frequency.

A third solution uses on/off controls in the feed track or delivery chute to control the operation of the feeder. A line of parts is stored in the external feed track and, when the line becomes short, the lower sensor activates the feeder, filling the line up to the level of the upper sensor which, in turn, shuts the feeder off.

Some of the more expensive vibratory-bowl feeders use silicon-controlled rectifier (SCR) drive systems, which can be coupled with accelerometer feedback to maintain a constant amplitude of vibration. This prevents the mean conveying velocity of the parts from increasing as the bowl empties.

3.10 SPIRAL ELEVATORS

A device commonly employed for elevating and feeding component parts is the spiral elevator. A typical spiral elevator is illustrated in Figure 3.16; it can be seen that the drive is identical to that used for a vibratory-bowl feeder. The helical track passes around the outside of a cylindrical tube. This device is not generally used to orient parts because the parts cannot readily be rejected back into the hopper bowl situated at the base of the elevator. Because the mode of conveying for the parts is identical to that obtained with a vibratory-bowl feeder, the results and discussion presented earlier, and the design recommendations made, will also apply to the spiral elevator.

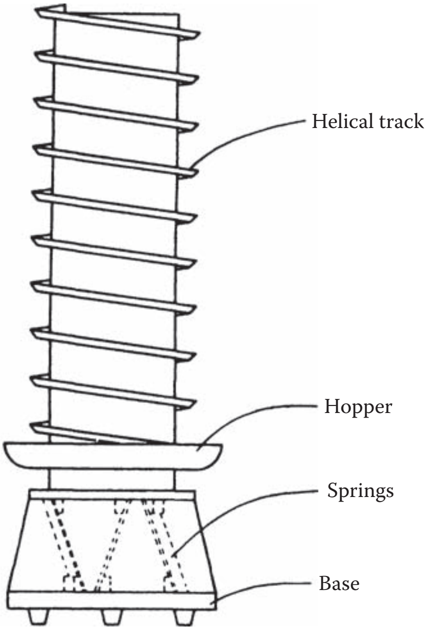


FIGURE 3.16 Spiral elevator.

3.11 BALANCED FEEDERS

One of the major problems in the application of vibratory feeding is the need to isolate the feeder vibrations from the structure of the assembly machine. For this reason, the base of a vibratory-bowl feeder is usually supplied with rubber feet. However, these feet provide the feeder with additional degrees of freedom and, if the bowl and tooling are not dynamically balanced, a rocking motion can be superimposed on the motions of the bowl. This rocking motion affects the vibration angle at the bowl track so that, in some regions of the track, the vibration angle is increased and, in some regions, it is decreased. This results in erratic behavior of the parts so that, along certain portions of the track, a high conveying velocity occurs while, along others, the parts slow down or even tend to stop.

The normal solution to this problem is to ensure that the bowl and its tooling are properly balanced. However, Yokoyama et al. [5] have proposed a variety of vibratory-feeder designs in which the horizontal components of the inertia forces cancel, resulting in a balanced design that minimizes the vibrations transmitted through the feeder supports. This approach is most easily described by referring to a recirculating vibratory feeder consisting of two linear vibratory tracks mounted side by side. Figure 3.17a shows a simple horizontal linear vibratory track, and it can be seen that the vertical components of any inertia forces would be carried equally by the two feet, whereas the horizontal components would superimpose a rocking motion. This rocking motion has the effect of increasing the conveying velocity at the beginning of the track and reducing it at the end of the track.

Figure 3.17b shows two such tracks mounted side by side in such a way that the horizontal components of the inertia forces cancel. Not only does this eliminate the rocking motion, but it provides a means of recirculating parts so that we have an alternative to the vibratory-bowl feeder, and one that enables us to place orienting devices on one of the tracks. Thus, parts in the correct orientation will pass through the devices to be delivered to the end of the track, whereas other parts are rejected onto the return track.

Commercial versions of this balanced feeder arrangement are available that are suitable for very small parts, such as surface-mount resistors. This balancing principle has also been applied successfully to a variety of vibratory-bowl feeder arrangments [5].

3.12 ORIENTATION OF PARTS

In an automatic assembly machine, the parts must be correctly oriented when they are fed to the workheads. The devices employed to ensure this fall into two groups: those that are incorporated in the parts feeder, which are usually referred to as *in-bowl tooling*; and those that are fitted to the chute between the feeder and the workhead, called *out-of-bowl tooling*. The devices used for in-bowl tooling very often work on the principle of orienting by rejection and may be termed *passive orienting devices*. With this type of device, only those parts that,

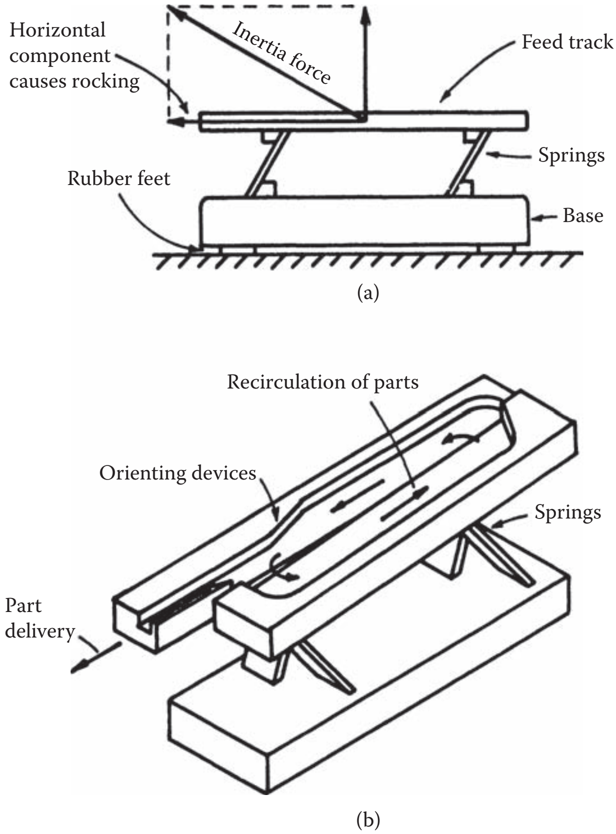


FIGURE 3.17 Balanced vibratory feeder.

by chance, are fed correctly oriented pass through the device, while the other parts fall back into the hopper or bowl. The rejected parts are then refed and make a further attempt to pass through the orienting device. In some cases, devices are fitted that can reorient parts. These may be termed *active orienting devices* and, although they are not as widely applicable, they have the advantage that no reduction in feed rate occurs as a result of the rejection of parts. In some cases, orienting devices are fitted between the parts feeder and the automatic workhead; with this system, rejected parts cannot easily be returned to the parts feeder, and orienting devices employed in this way are usually of the active type.

The following section describes some of the more common orienting devices and tooling employed in feeders for automatic assembly.

3.13 TYPICAL ORIENTING SYSTEM

Of all the various types of feeding devices, vibratory-bowl feeders allow by far the greatest flexibility in the design of orienting devices. Figure 3.18 shows the

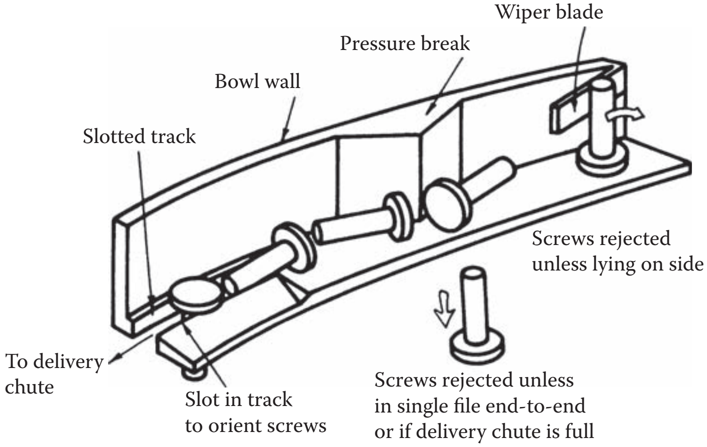

Wiper blade
Pressure break
Bowl wall
Slotted track
Screws rejected unless lying on side
To delivery chute
Slot in track to orient screws
Screws rejected unless in single file end-to-end or if delivery chute is full

FIGURE 3.18 Orientation of screws in vibratory-bowl feeder.

orienting system commonly employed to orient screws in a vibratory-bowl feeder. In this arrangement, the first device, a wiper blade, rejects all the screws not lying flat on the track. The gap below the blade is adjusted so that a screw standing on its head or a screw resting on the top of others is either deflected back into the bowl or made to lie flat on the track. Clearly, the wiper blade can be applied here only if the length of the screw is greater than the diameter of its head. The next device, a pressure break, allows screws to pass only in single file and only with either head or shank leading. Screws being fed in any other attitude will fall off the narrow track and back into the bowl at this point. The pressure break also performs another function: If the delivery chute becomes full, excess parts are returned to the bottom of the bowl at the pressure break, and congestion in the chute is therefore avoided. The last device consists of a slot in the track that is sufficiently wide to allow the shank of the screw to fall through while retaining the screw head. Screws arriving at the slot either with the shank leading or with the head leading are therefore delivered with the shank down, supported by the head. In this system for orienting screws, the first two devices are passive and the last is active.

Although the devices described above are designed for parts of a certain shape, two of them have wide application in vibratory-bowl feeding. First, a pressure break is usually necessary because most feeders are adjusted to overfeed slightly in order to ensure that the workhead is never "starved" of parts. In this situation, unless a level-sensing device controlling the feeder output is attached to the delivery chute, the delivery chute is always full, and a pressure break provides a means of preventing congestion at its entrance.

Second, the wiper blade is a convenient method of rejecting parts that are resting on top of others. In a vibratory-bowl feeder, this often occurs because of the pushing action of parts traveling up the track. However, care must be taken in applying the wiper blade because thin parts may have a tendency to jam under

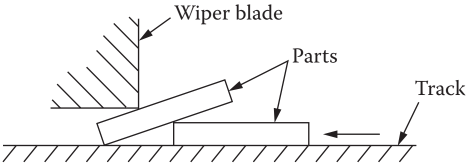


FIGURE 3.19 Thin parts jammed under wiper blade.

the blade, as illustrated in Figure 3.19. The tendency for this jamming to occur can be reduced by arranging the blade so that it lies at an acute angle to the bowl, as shown in Figure 3.18. In some cases, an alternative approach is necessary, and this is illustrated in Figure 3.20, which shows the orienting device commonly employed to orient washers. It can be seen that a portion of the track is arranged to slope sideways and down toward the center of the bowl. A small ledge is provided along the edge of this section of the track to retain those washers that are lying flat and in single file. Other washers will slide off the track and into the bowl. With a device of this type, where the parts are rotated as they are fed, it is often necessary to arrange the design of the track to ensure that the path of the center of gravity of the part is not raised rapidly; otherwise, a serious reduction in feed rate may occur.

Figure 3.21 shows a refinement made in the orienting device described in the preceding paragraph. In this case, machined washers may be oriented by providing a ledge sufficiently large to retain a washer being fed base down (Figure 3.21a) but too small to retain a washer being fed base up (Figure 3.21b).

Figure 3.22 illustrates a common type of orienting device known as a *cutout*, where a portion of the track has been cut away. This device makes use of the difference in shape between the top and the base of the part being fed. Because

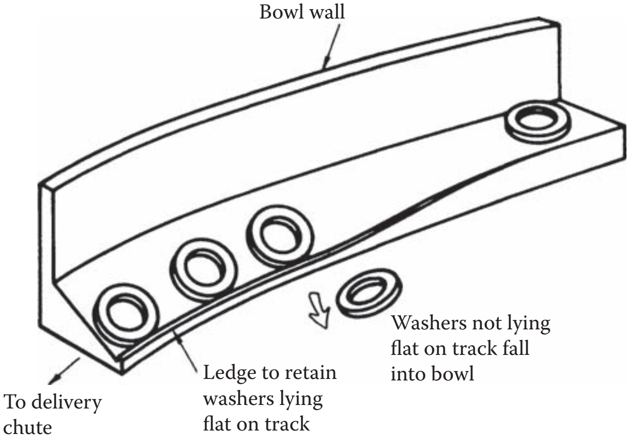

Bowl wall
Washers not lying flat on track fall into bowl
Ledge to retain washers lying flat on track
To delivery chute

FIGURE 3.20 Orientation of washers in vibratory-bowl feeder.

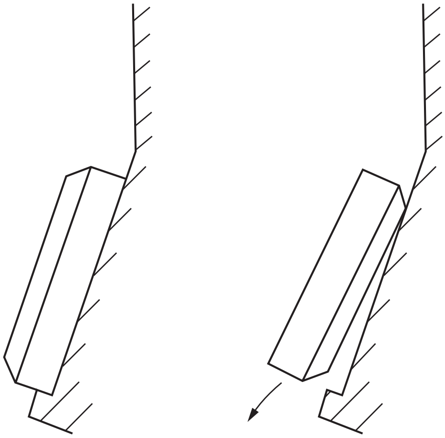

(a) Washer accepted (b) Washer rejected

FIGURE 3.21 Orientation of machined washers.

of the width of the track and the wiper blade, the cup-shaped part can only arrive at the cutout resting on its base or on its top. It can be seen from Figure 3.22 that the cutout has been designed so that a part resting on its top falls off the track and into the bowl, whereas a part resting on its base passes over the cutout and moves onto the delivery chute.

Figure 3.23 shows another application of a cutout, in which the area covered by the top of a part is very much smaller than the area covered by its base. In this case, a V-shaped cutout rejects any part resting on its top.

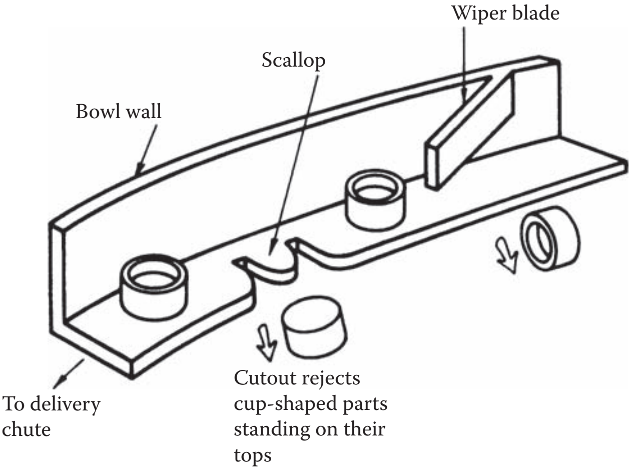


FIGURE 3.22 Orientation of cup-shaped parts in vibratory-bowl feeder.

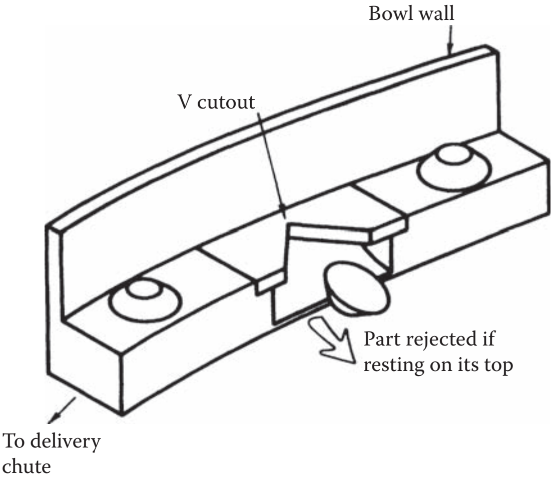


FIGURE 3.23 Orientation of truncated cones in vibratory-bowl feeder.

Figure 3.24 shows an example in which U-shaped parts are oriented. With parts of this type, it is convenient to feed them supported on a rail. In this case, some of the parts climb onto the rail and pass to the delivery chute. The remainder falls into the bowl, either directly or through a slot between the rail and the bowl wall.

Figure 3.25 shows a narrowed-track orienting device that is generally employed to orient parts lengthwise end to end while permitting only one row to pass. Finally, Figure 3.26 shows a wall projection and narrowed-track device used to feed and orient parts with steps or grooves, such as short, headed parts.

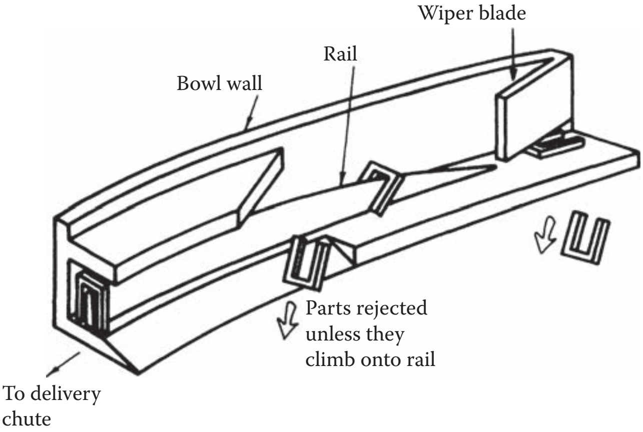


FIGURE 3.24 Orientation of U-shaped parts in vibratory-bowl feeder.

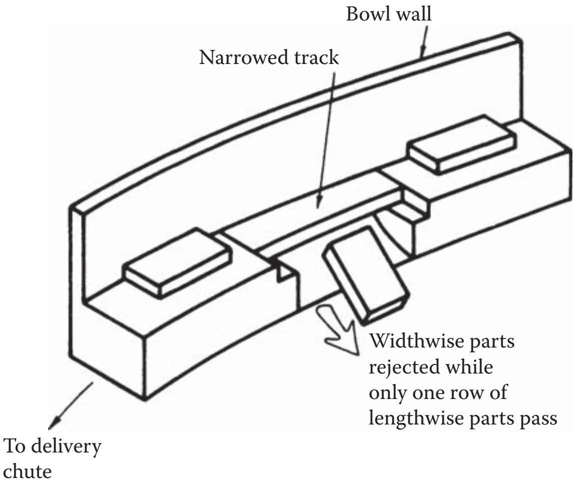

Bowl wall
Narrowed track
Widthwise parts rejected while only one row of lengthwise parts pass
To delivery chute

FIGURE 3.25 Narrowed track.

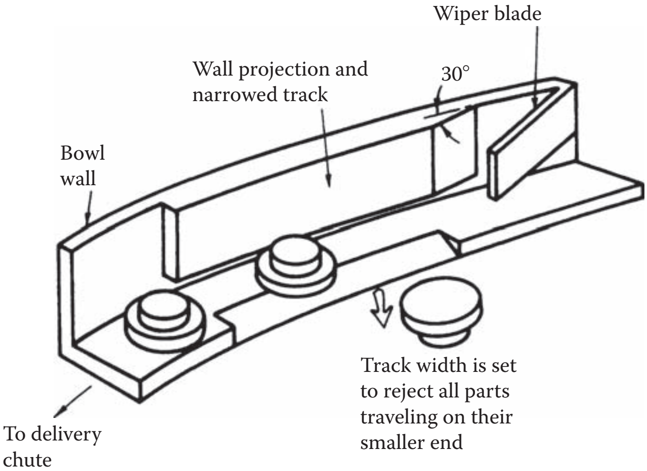

Wiper blade
Wall projection and narrowed track
30°
Bowl wall
Track width is set to reject all parts traveling on their smaller end
To delivery chute

FIGURE 3.26 Wall projection and narrowed track.

A short, headed part traveling on its larger end passes through the device, but other orientations are rejected back into the bowl.

Data on the design of orienting devices are presented in Appendix D.

3.14 EFFECT OF ACTIVE ORIENTING DEVICES ON FEED RATE

Sometimes, a part used on an assembly machine can have only a single orientation but, more often, the number of possible orientations is considerably greater. If, for example, a part had eight possible orientations and the probabilities of the various orientations were equal and, further, if only passive orienting devices were used to orient the parts, the feed rate of oriented parts would be only one-eighth of the feed rate of unoriented parts. It is clear that if active orienting devices could be utilized, the feed rate of oriented parts could be considerably increased.

To illustrate this point, consider the orienting system shown in Figure 3.27 for feeding rectangular blocks. At one point, the width of the track is such that blocks can be fed only with their long axes parallel to the direction of motion. Also, a wiper blade is arranged so that blocks lying flat or standing on their sides will be accepted. It is assumed in this example that the width of a block is less than twice its thickness. Finally, an active orienting device in the form of a tapered element ensures that blocks lying flat will be turned to stand on their sides. With this arrangement, all the blocks fed into the track with their long axes parallel to the conveying direction will be fed from the bowl. If, however, the active orienting device was not part of the system and the wiper blade had been arranged to accept only the blocks lying flat on the track, a larger proportion of blocks would have been rejected, with a consequent reduction in feed rate.

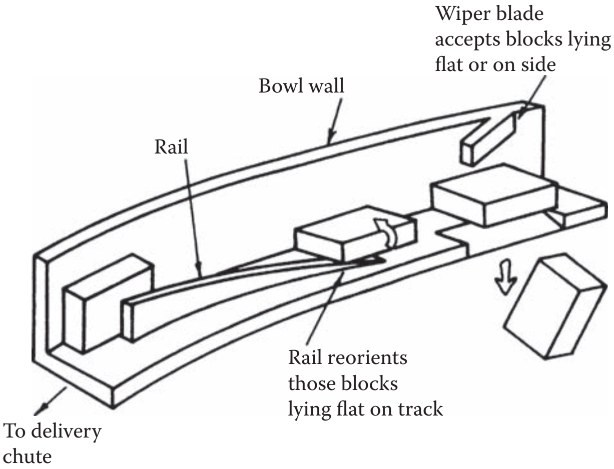


FIGURE 3.27 Orientation of rectangular blocks in vibratory-bowl feeder.

3.15 ANALYSIS OF ORIENTING SYSTEMS

To determine the effect of certain aspects of part geometry on the efficiency with which the part can be fed and oriented, consider several parts having the same basic shape but different sizes [6]. Figure 3.28 shows a family of cup-shaped parts that take the form of plain cylinders, with a blind hole drilled axially from one end. These parts have the same diameter, 12.7 mm, with an 11.7-mm-diameter square bottom hole drilled from one end to a depth of 0.718 times the length of the part. It can be shown that, for all these parts, the center of mass is positioned at the bottom of the hole; the only geometric variable necessary to describe the part is its length-to-diameter ratio.

For a bowl feeder having a track that ensures single-file feeding of these parts, only four orientations of the part need to be considered. These orientations are shown in Figure 3.29 and are keyed *a*, b_1, b_2, and *c*. Orientation *a* shows the part fed standing on its base (that is, heavy end down). Orientations b_1 and b_2 show the part fed on its side, either heavy end first (b_1) or light end first (b_2). Finally, orientation *c* shows the part fed heavy end up.

Before a study of the design of an orientation system for these parts can be made, it is necessary to know the probabilities with which these four orientations would initially occur. This information can then be used as the input to the orienting system analysis. Figure 3.30 presents the results of experimental and theoretical work. In the experiments, each part was repeatedly thrown onto a flat horizontal aluminum surface, and the resulting final resting aspect was noted for each trial. In this experiment, it is not possible to distinguish between orientations b_1 and b_2 because the direction of feeding is not defined. For this reason, the term *natural resting aspect* is employed, which is meant to describe the way in which a part can rest on a horizontal surface. Thus, natural resting aspect *a* designates

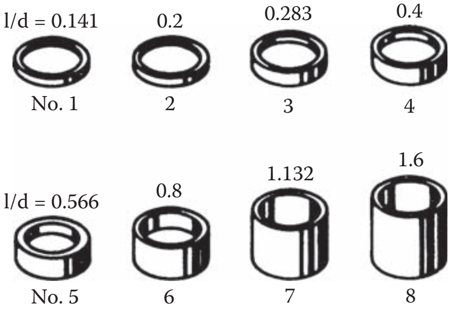


FIGURE 3.28 Parts used in the experiment. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

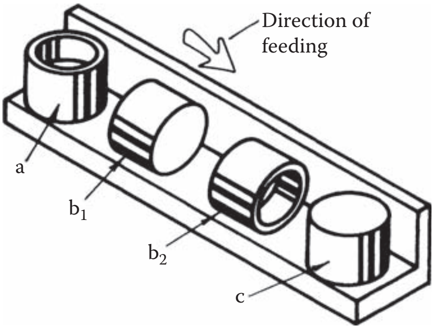


FIGURE 3.29 Orientations of cup-shaped parts. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

parts resting on their bases, *b* designates parts resting on their sides, and *c* refers to parts resting with their heavy ends up. Those parts that come to rest on their sides will, when fed, separate about equally into the two orientations b_1 and b_2 described above. It can be seen from Figure 3.30 that, for example, the probability that a cup-shaped part having a length-to-diameter ratio of 0.8 will come to rest on its base (natural resting aspect *a*) is 0.4. Each experimental value in Figure 3.30 represents the results of at least 250 trials and has 95% confidence limits of less than ± 0.05.

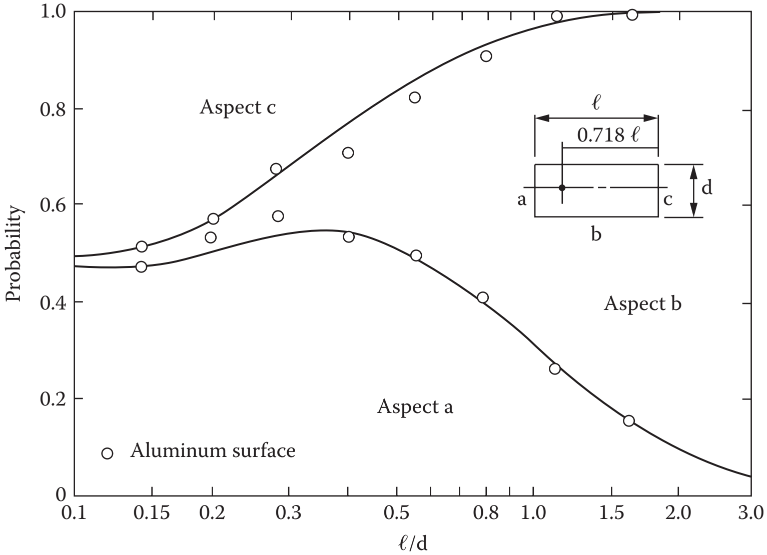


FIGURE 3.30 Distribution of natural resting aspects. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

The basis of a theoretical study of the distributions of natural resting aspects of parts is described later in this chapter. The solid lines shown in Figure 3.30 are based on theoretical values and can be seen to agree closely with the experimental results.

3.15.1 Orienting System

A system for orienting cup-shaped parts is shown in Figure 3.31. It consists of one active device, a step; and two passive devices: a scallop and a sloped track with a ledge. The system is designed to deliver a part in orientation *a* (i.e., on its base).

In the orientation process, the parts first encounter the step device, whose purpose is to increase the proportion of parts in orientation *a*. This increase is achieved by arranging a step height that does not affect many of the parts in orientation *a* but reorients some of the parts in orientations b_1 or *c* into orientation *a* as they pass over the step.

The remaining passive devices are simply designed to ensure that all parts in orientations b_1, b_2, and *c* are rejected back into the bowl. These rejected parts later make further attempts to filter through the orienting system.

The first of the passive devices, the scallop cutout, ensures rejection of a part in orientation *c*. Its design is based on data regarding the feeding motion of the part when the horizontal amplitude of vibration at the bowl wall was set at 1.0 mm with a vibration angle of 5°. The motion of the part under these conditions is shown in Figure 3.32 and was obtained using a computer program similar to that described by Redford and Boothroyd [1]. It can be seen from the figure that the part slides forward a distance of 0.86 mm after hopping and then slides 0.91

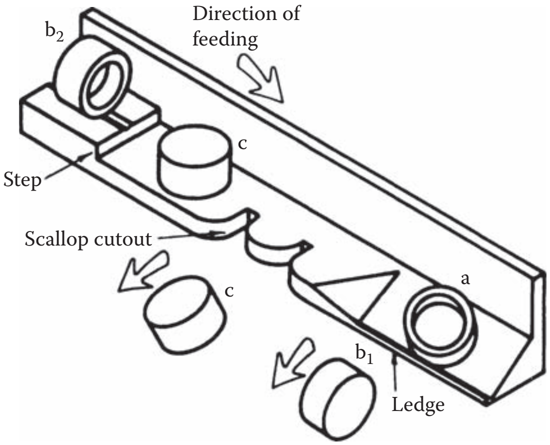


FIGURE 3.31 Experimental orienting system. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

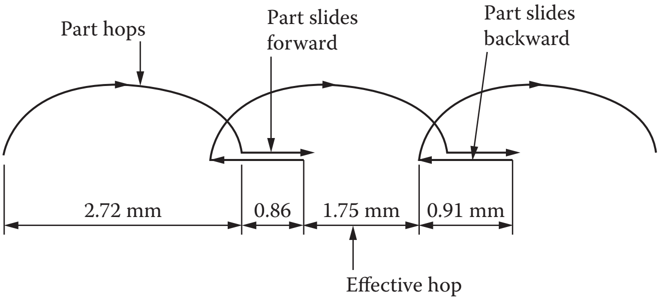


FIGURE 3.32 Motion of part relative to track during experiments. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

mm backward before hopping again. Although the distance the part hops is 2.72 mm, the maximum gap in the track that any point on the undersurface of the part can negotiate is 1.75 mm. With this information, it is possible to design the scallop device so that parts in orientation *a* are always supported, regardless of where they are situated on the device, whereas those parts in orientation *c* will, at some point, be situated in a position where they cannot be supported and will fall off the track into the bowl. Experiments [6] show that a small proportion of those parts in orientations b_1 and b_2 are also rejected by this device, but this does not affect the performance of the system because the next device will, in any case, reject parts in both these orientations.

The second passive device, the sloped track with a ledge, is designed to reject all those parts in orientations b_1 and b_2. The ledge retains parts in orientation *a* but does not prevent parts in orientations b_1 and b_2 from rolling off the track and back into the bowl.

The only orienting system variable considered here is the height of the active step orienting device and, in order to perform an optimal design analysis, it is necessary to carry out an experimental program to measure the effect of various step heights on different orientations of each of the eight specimens. Typical results of such experiments are presented in Figure 3.33, which shows the effects of feeding a part in each of its four initial orientations, over the step, with step heights varying from zero to a maximum of 7 mm. It was found that, for step heights greater than 7 mm, the parts would bounce erratically upon landing on the track below the step, an effect that would be unacceptable in practice.

3.15.2 METHOD OF SYSTEM ANALYSIS

The object of an analysis of a bowl-feeder orienting system is to design each device so that the highest value for the efficiency of the complete system is obtained. The efficiency of the system is defined as the number of properly oriented parts delivered by the system, divided by the number of parts entering the system.

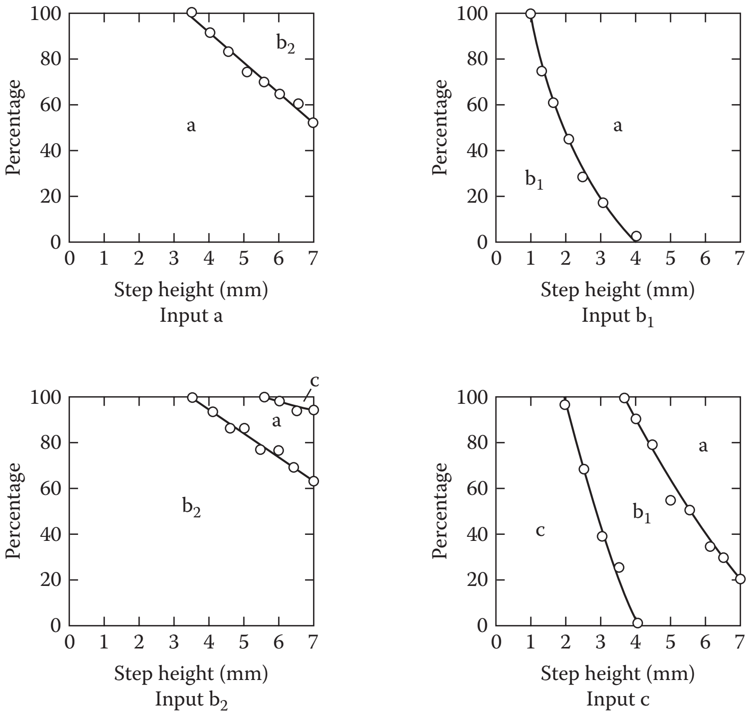
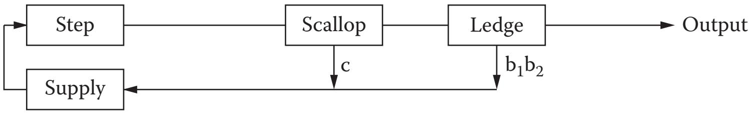


FIGURE 3.33 Effect of step on part 7. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

To calculate this efficiency for a system of orienting devices, a matrix technique has been developed [7]. Each device is represented by a matrix whose number of rows and columns depends on the number of orientations in the devices' respective input and output. If these matrices are multiplied in the order in which the parts encounter the devices, the resulting single-column matrix represents the performance of the system. If this matrix is then premultiplied by a single-row matrix representing the initial distribution of orientations of the part, the efficiency of the system is obtained.

Figure 3.34 shows a schematic diagram for the present system, together with the appropriate matrices. The terms in the matrix that represent the step device are only symbolic. The term AA indicates the proportion of those parts in orientation a that will remain in orientation a, AB_1 represents those parts in orientation a that are reoriented into b_1, and so on. In the matrix for the scallop device, q_1 and q_2 represent the proportion of parts that enter the device in orientations b_1 and b_2, respectively, and exit in the same orientation. For part 7 and a step height of 7 mm, the step orienting device matrix becomes



$$\begin{array}{c} \text{Step} \\ \begin{array}{c|cccc|} & a & b_1 & b_2 & c \\ \hline a & AA & AB1 & AB2 & AC \\ b_1 & B1A & B1B1 & B1B2 & B1C \\ b_2 & B2A & B2B1 & B2B2 & B2C \\ c & CA & CB1 & CB2 & CC \end{array} \end{array} \quad \begin{array}{c} \text{Scallop} \\ \begin{array}{c|ccc|} & a & b_1 & b_2 \\ \hline a & 1 & 0 & 0 \\ b_1 & 0 & q_1 & 0 \\ b_2 & 0 & 0 & q_2 \\ c & 0 & 0 & 0 \end{array} \end{array} \quad \begin{array}{c} \text{Ledge} \\ \begin{array}{c|c|} & a \\ \hline a & 1 \\ b_1 & 0 \\ b_2 & 0 \end{array} \end{array} \quad \begin{array}{c} \text{Output} \\ \begin{array}{c|c|} & a \\ \hline a & AA \\ b_1 & B1A \\ b_2 & B2A \\ c & CA \end{array} \end{array}$$

FIGURE 3.34 Orienting system analysis. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

$$\begin{array}{c|cccc|} & a & b_1 & b_2 & c \\ a & 0.50 & 0 & 0.50 & 0 \\ b_1 & 1.00 & 0 & 0 & 0 \\ b_2 & 0.30 & 0 & 0.64 & 0.06 \\ c & 0.80 & 0.20 & 0 & 0 \end{array} \tag{3.18}$$

and the resulting system matrix is

$$\begin{array}{c|cccc|} & a & b_1 & b_2 & c \\ a & 0.50 & 0 & 0.50 & 0 \\ b_1 & 1.00 & 0 & 0 & 0 \\ b_2 & 0.30 & 0 & 0.64 & 0.06 \\ c & 0.80 & 0.20 & 0 & 0 \end{array} \begin{array}{|ccc|} a & b_1 & b_2 \\ 1 & 0 & 0 \\ 0 & q_1 & 0 \\ 0 & 0 & q_2 \\ 0 & 0 & 0 \end{array} \begin{array}{|c|} a \\ 1 \\ 0 \\ 0 \\ 0 \end{array} = \begin{array}{|c|} a \\ 0.50 \\ 1.00 \\ 0.30 \\ 0.80 \end{array} \tag{3.19}$$

This result means that 50% of those parts that enter the system in orientation a exit in orientation a, 100% of those parts that enter in orientation b_1 exit in orientation a, and so on.

From Figure 3.30, the initial distribution matrix for part 7 is

$$\begin{bmatrix} a\ b_1\ b_2\ c \end{bmatrix} = \begin{bmatrix} 0.27\ 0.35\ 0.35\ 0.03 \end{bmatrix} \tag{3.20}$$

Thus, premultiplying the system matrix, Equation 3.19, by the input distribution matrix, Equation 3.20, gives

$$\begin{bmatrix} 0.27\ 0.35\ 0.35\ 0.03 \end{bmatrix} \begin{bmatrix} 0.50 \\ 1.00 \\ 0.30 \\ 0.80 \end{bmatrix} = 0.61$$

which means that, under these conditions, the efficiency of the system is 61%. Hence, if the bowl was set to feed parts at a rate of 10 parts/min, the mean delivery rate of parts in orientation *a* would be 6.1 parts/min.

3.15.3 OPTIMIZATION

To optimize the design of this system, it is necessary to determine the step height that gives the maximum efficiency for each of the eight parts. The simplest method is to calculate the system efficiency for increments of step height within the practical range. The results of this procedure are shown in Figure 3.35 and Figure 3.36, where it can be seen that the maximum efficiency for five of the parts occurs at the maximum allowable step height of 7 mm. These maxima are plotted in Figure 3.37 (curve *B*) and compared with the initial distribution of parts in orientation *a* (curve *A*). This initial distribution is the same as the system efficiency that would be obtained if the step device had not been included in the system, and the figures show clearly the advantages of including the step device. In many cases, the efficiency of the system is almost doubled; in other words, the output rate of oriented parts would be almost doubled. Because such significant advantages of including the step device in the system can be demonstrated, it is of interest to consider the effect of including a further step device. In this case, a further variable is introduced, and the upper curve shown in Figure 3.37 is obtained. In all cases, it can be seen that the overall maximum efficiency is achieved with parts having a length-to-diameter ratio *l*/*d* of 0.4.

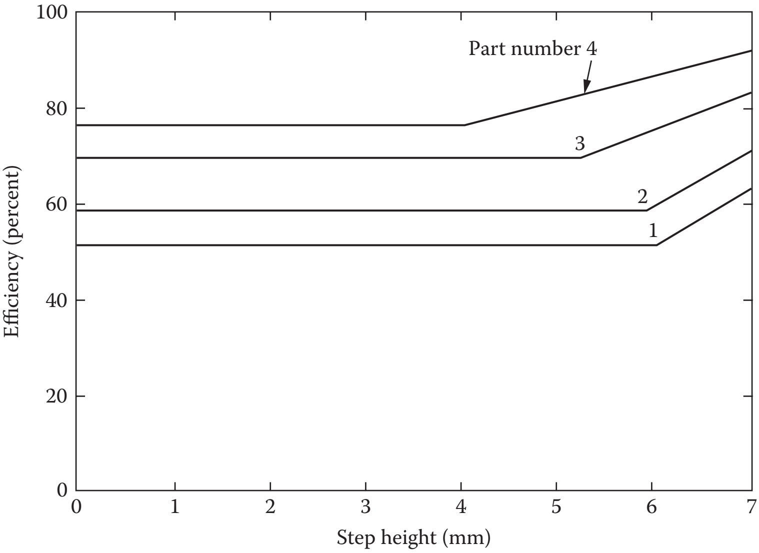


FIGURE 3.35 Effect of step height on efficiency (parts 1, 2, 3, and 4). (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

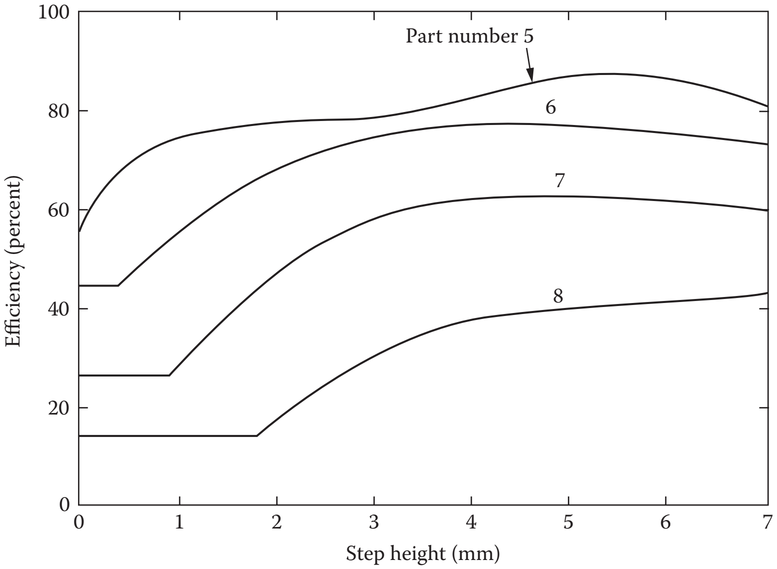


FIGURE 3.36 Effect of step height on efficiency (parts 5, 6, 7, and 8). (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

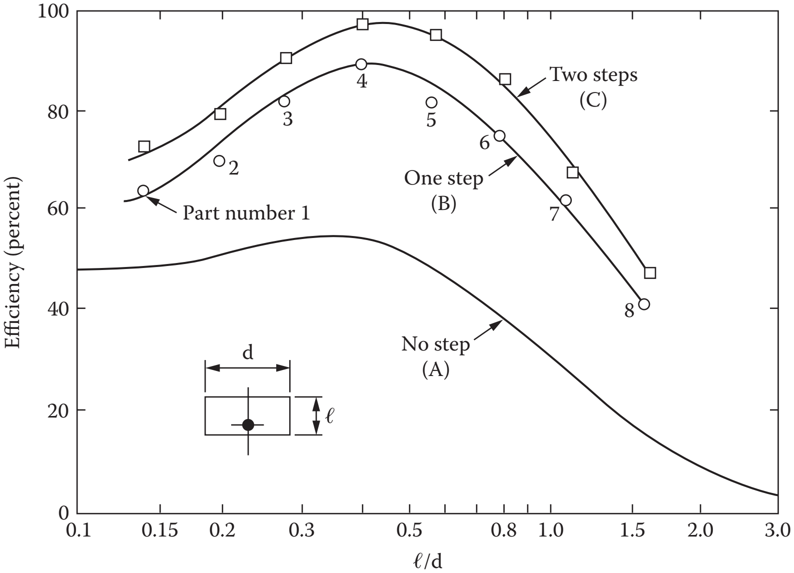


FIGURE 3.37 Effect of part shape on efficiency of orienting system. (From Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972. With permission.)

3.16 PERFORMANCE OF AN ORIENTING DEVICE

In the preceding section, it was seen that to optimize the design of the orienting system for cup-shaped parts, it was necessary to determine the step height that would provide the maximum efficiency. The information employed to determine the performance of the step orienting device was empirical. It would be most useful in investigations involving the optimization of an orienting system if theoretical expressions were available that described with sufficient accuracy the performance of the orienting device. The present section describes the analysis of one of the passive orienting devices introduced earlier: a V cutout (Figure 3.23) used for the orientation of truncated cone-shaped parts. It can be seen from Figure 3.23 that, with a properly designed device, those parts being fed base uppermost will be rejected, whereas those parts being fed base down will be accepted and allowed to proceed to the outlet chute.

Because the height of the part has no effect on the performance of the device, the only parameters necessary to describe its important characteristics are the radius R of the base and the radius r of the top. The symmetrical orienting device may also be described completely by using only two parameters: the half-angle θ of the cutout and the distance b from the apex of the cutout to the bowl wall.

During vibratory feeding, the part proceeds along the track by a combination of discrete sliding motions either backward or forward or both and, under certain conditions, by a forward hop. All the motions occur sequentially during each cycle of the vibratory motion of the bowl. During each cycle, when the conditions are such that the part hops, there will usually be a distance along the track, denoted by J, where the part does not touch the track. Therefore, J is the smallest gap or slot in the track that will reject all particles that travel with this particular motion. For vibratory conditions that produce relatively small sliding motions compared to the hop, the motion can be characterized by a series of equal hops, each of distance J.

The object of the design of a V cutout would be to determine the values of the parameters θ and b such that, for a given part (i.e., for given values of R and r) and for a given feeding characteristic (i.e., given J), all the parts fed on their tops would be rejected, and a maximum of those fed on their bases would be accepted.

3.16.1 ANALYSIS

Figure 3.38 shows two limiting conditions for the position of a part resting on its top. In the first position, the center of the part lies at P on the edge of the cutout. Thus, if the part comes to rest momentarily just to the right of P, it will be rejected. The second limiting condition places the center of the part at Q, and the edge of the part is just supported at D by the edge of the cutout. Thus, if the part contacts the track with its center anywhere between P and Q, it will be rejected. Two similar limiting conditions not shown in the figure will exist to the right of the cutout centerline, and these positions may be deduced from the symmetry of the situation.

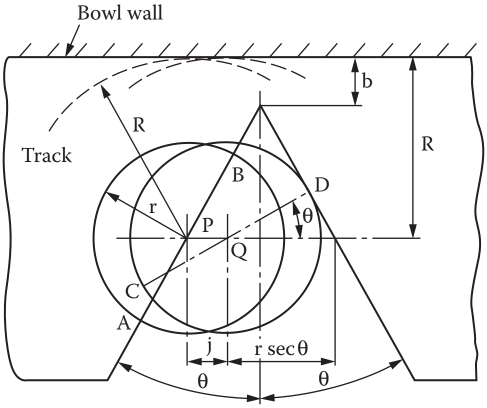


FIGURE 3.38 Determination of j for small cutout angles.

It is clear that, for a part traveling from left to right (Figure 3.38) in a series of hops, the probability that its center will fall in the space between P and Q (and thus cause rejection) is given by j/J, where j is the distance between P and Q, and J is the length of each hop.

For those parts that negotiate the gap between P and Q, the probability that they will clear the first gap is $(1 - j/J)$ and the probability that they will be rejected in the similar gap lying to the right of the cutout centerline, is (j/J). Hence, the total probability R_e that a part will be rejected in one of the two gaps is

$$R_e = j/J + (1 - j/J)j/J = 2(j/J) - (j/J)^2 \tag{3.21}$$

For the conditions illustrated in Figure 3.38,

$$j = 2(R - b)\tan\theta - r\sec\theta \tag{3.22}$$

For large cutout angles, Equation 3.22 does not always apply because when the top of the part is supported at D by the right-hand edge of the cutout, point C, diametrically opposite D, may be to the right of the left-hand edge of the cutout. Thus, a part in this situation will be rejected, and an alternative limiting condition will arise. In this case, point P is unchanged, but point Q is found by arranging for the diameter CD of the part to be just supported between the edges of the cutout. From Figure 3.39,

$$j = (R - b)\tan\theta - x \tag{3.23}$$

and

$$x = r\cos\alpha - [(R - b) - r\sin\alpha\tan\theta] \tag{3.24}$$

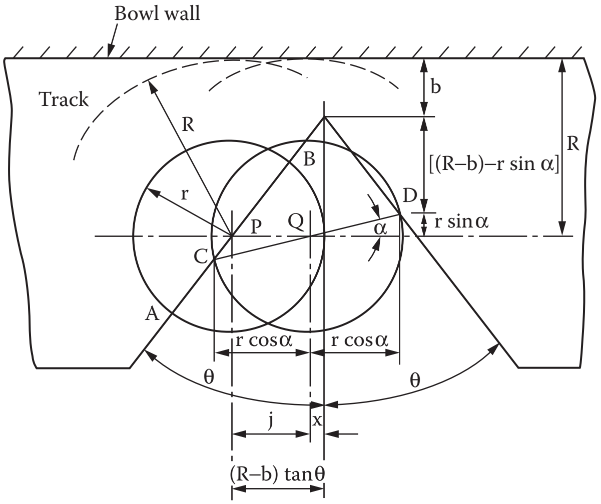


FIGURE 3.39 Determination of *j* for large cutout angles.

Also,

$$x = [(R - b) + \sin\alpha]\tan\theta - r\cos\alpha \tag{3.25}$$

Eliminating α from Equation 3.24 and Equation 3.25 gives

$$x = \tan\theta[r^2 - (R - b)^2\tan^2\theta]^{1/2} \tag{3.26}$$

Finally, substituting Equation 3.26 into Equation 3.23 gives

$$j = \tan\theta\{(R - b) - [r^2 - (R - b)^2\tan^2\theta]^{1/2}\} \tag{3.27}$$

The value of b at which Equation 3.22 becomes invalid and Equation 3.27 must be applied can be found by arranging for CD in Figure 3.39 to lie at right angles to the right-hand edge of the cutout. Under these conditions, α becomes equal to θ, and eliminating x from Equation 3.24 and Equation 3.25 gives

$$(R - b) = r\cos\theta\cot\theta \tag{3.28}$$

and, thus, from Equation 3.22 or Equation 3.27,

$$j = r(2\cos\theta - \sec\theta) \tag{3.29}$$

It can readily be shown that, for $\theta \geq 45°$, Equation 3.27 always applies.

It is convenient to eliminate one variable from the foregoing expressions by dividing through by R and thereby writing the parameters in dimensionless form.

Defining $r_0 = r/R$, $b_0 = b/R$, $j_0 = j/R$, and $J_0 = J/R$, the following equation is obtained for the rejection R_e of parts:

$$R_e = 2(j_0/J_0) - (j_0/J_0)^2 \tag{3.30}$$

where

$$j_0 = \tan\theta\{(1-b_0) - [r_0^2 - (1-b_0)^2 \tan^2\theta]^{1/2}\} \tag{3.31}$$

unless $\theta < 45°$ and $b_0 > (1 - r_0 \cos\theta \cot\theta)$, in which case,

$$j_0 = 2(1 - b_0)\tan\theta - r_0 \sec\theta \tag{3.32}$$

These equations are presented in graphical form in Figure 3.40 for a cutout having a half-angle of 30° and for a part where r_0 is 0.8.

The figure shows how the theoretical rejection rate R_e varies as the parameter b_0 is changed for a given value of the distance J_0 hopped by the part during each vibration cycle. The figures for the case in which the part is being fed on its base were obtained by setting r_0 equal to unity. A negative b refers to the case in which the apex of the cutout lies outside the interior surface of the bowl wall.

It can be seen from the figure that, as the parameter b_0 is gradually decreased, a condition is eventually reached at which the unwanted parts (those being fed on their tops) will start to be rejected. On further decreases in b_0, a point will be reached at which all these parts will be rejected. Similar situations will arise for the wanted parts but for lower values of b_0. Eventually, a value of b_0 will be reached at which all the parts will be rejected. Clearly, in practice, it will be

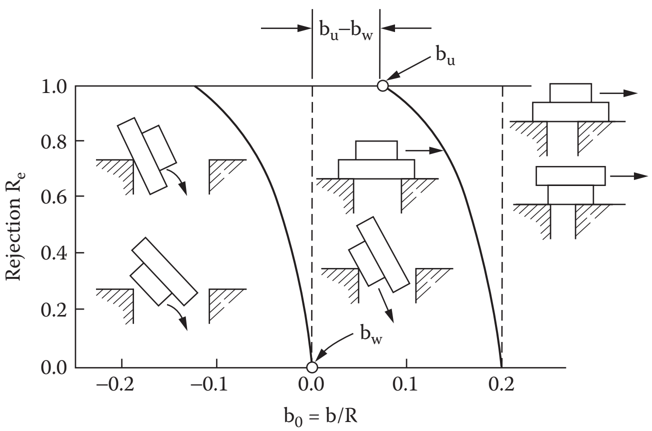


FIGURE 3.40 Effect of b_0 on rejection of parts: θ = 30 deg, J_0 = 0.15.

necessary to choose a situation in which all the unwanted parts will be rejected, even at the expense of rejecting some of the wanted parts.

After defining the largest value of b_0 for which all the unwanted parts are rejected as b_u and the smallest value at which all wanted parts are accepted as b_w, it can be stated that the best conditions would be those that resulted in the largest value of $(b_u - b_w)$. This would give the greatest working range for a given part and for given feeding conditions.

It is of interest to study how the magnitudes of b_u and b_w are affected by changes in the design parameters. The value of b_u is obtained by setting R_e equal to unity in Equation 3.30 with the appropriate equation for j_0, Equation 3.31 or Equation 3.32; the value of b_w is obtained by setting R_e equal to zero and r_0 equal to unity.

Thus, after rearrangement, when θ ≥ 45°,

$$b_u = 1 - \cos^2\theta\,[J_0 \cot\theta + (r_0^2 \sec^2\theta - J_0^2)^{1/2}] \tag{3.33}$$

$$b_w = 1 - \cos\theta \tag{3.34}$$

when θ ≤ 45°,

$$b_u = 1 - 0.5\,J_0 \cot\theta - 0.5\,r_0 \operatorname{cosec}\theta \tag{3.35}$$

$$b_w = 1 - 0.5 \operatorname{cosec}\theta \tag{3.36}$$

unless $b_u < (1 - r_0 \cos\theta \cot\theta)$, in which case it is given by Equation 3.33 and b_w is given by Equation 3.36. These equations are plotted in Figure 3.41 and illustrate the effects of θ and J_0.

This theory has been developed for an idealized situation in which the part proceeds along the track by hopping. However, in reality, both hopping and sliding occur. It can be shown that, although this would affect Equation 3.30, and hence the shapes of the curves in Figure 3.40, the values of b_u and b_w would be unchanged.

Values of the working range $(b_u - b_w)$ obtained from Equation 3.33 to Equation 3.36 are plotted against θ in Figure 3.42. It can be seen that, for larger values of J_0, an optimum condition exists that gives the maximum working range. Further, at low values of θ, the magnitude of the working range becomes very sensitive to changes in J_0. Because most vibratory feeders operate at the same frequency, a large value of J_0 implies a high conveying velocity. In practice, it would clearly be desirable to choose conditions that give minimum sensitivity to changes in the feeding parameters and yet give the maximum working range for a reasonably large value of J_0.

The procedure used to obtain the experimental values for b_u and b_w, which are presented in Figure 3.41, is outlined by Boothroyd and Murch [8]. It is seen in Figure 3.41 that the results for b_u show good agreement with the theory over

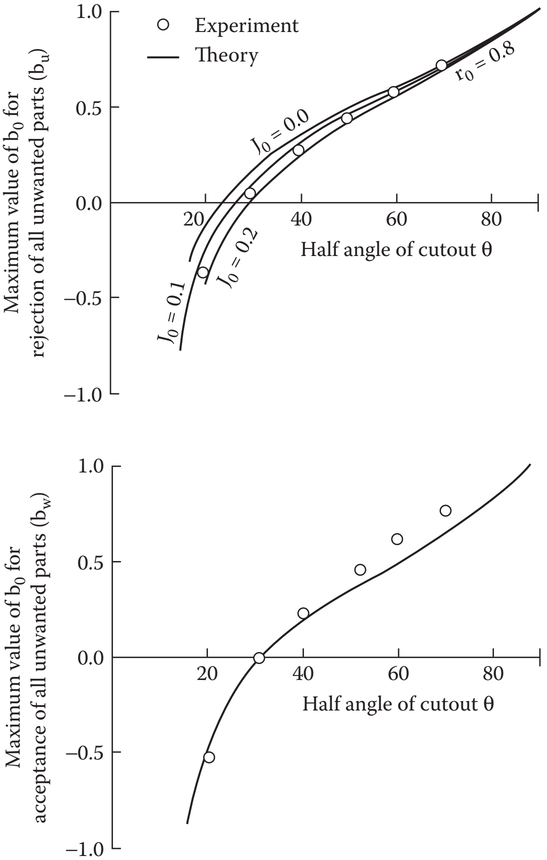


FIGURE 3.41 Effect of θ on values of b_u and b_w. (From Boothroyd, G. and Murch, L.E., Performance of an Orienting Device Employed in Vibratory-Bowl Feeders, *Transactions of the ASME, Journal of Engineering for Industry*, Aug. 1970. With permission.)

the whole range of cutout angles when J_0 is set equal to 0.15. The experimental values for b_w show good agreement with the theory only at small cutout angles. For larger cutout angles, the experimental value is always larger.

Ideally, in the design of a V-cutout orienting device, the pertinent data regarding the vibrating motion of the bowl feeder could be used to estimate the value of J_0, employing the results presented earlier in this chapter. Subsequently, using Figure 3.42, the half-angle θ of the cutout that gives the best value for the working range could be chosen. From this figure, when $J_0 \leq 0.1$, the smaller the value of θ, the larger the working range. However, small cutout angles can present a practical problem: Parts that are rejected may not be deflected properly from the bowl track and may interfere with the behavior of the parts that follow. Thus, the angle chosen should be that which gives the best working range and yet provides for adequate deflection of rejected parts.

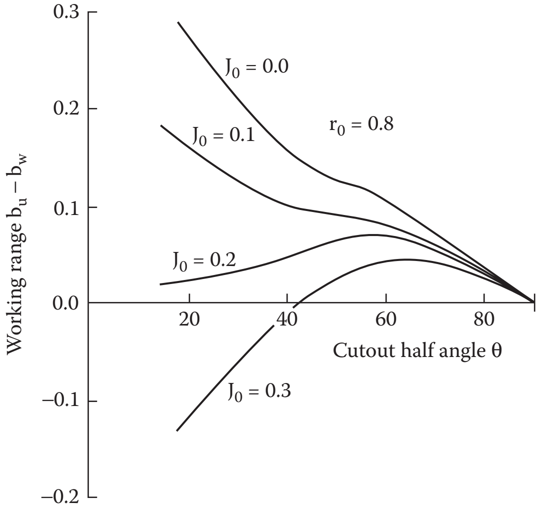


FIGURE 3.42 Effect of cutout angle on the working range. (From Boothroyd, G. and Murch, L.E., Performance of an Orienting Device Employed in Vibratory-Bowl Feeders, *Transactions of the ASME, Journal of Engineering for Industry*, Aug. 1970. With permission.)

Because it is essential that all the unwanted parts be rejected, the value of b_0 (which defines the position of the cutout apex) must be less than b_u. The value of b_u can be found from either Equation 3.33 or Equation 3.35, whichever is appropriate.

In practice, this method will result in an effective orienting device but not necessarily the most efficient one. If, for the larger cutout angles, the experimental values of b_w were significantly larger than that predicted by theory, the corresponding working ranges ($b_u - b_w$) would be negative. Thus, when the cutout is designed so that all the unwanted parts are rejected, some of the wanted parts will also be rejected. This reduces the output and can result in low efficiency.

In view of these observations, the recommended procedure would be to choose a value of θ less than 45° but large enough to give acceptable levels of deflection of the parts into the bowl and then determine b_u from the appropriate equation. Such an orienting device would have a positive working range when J_0 is less than 0.2 and thus have an efficiency of 100%.

3.17 NATURAL RESTING ASPECTS OF PARTS FOR AUTOMATIC HANDLING

In order to analyze the complete system for orienting cup-shaped parts (Figure 3.31), it was necessary to know the probabilities with which the various orientations would initially occur, and Figure 3.30 presented the experimental and theoretical results of the distribution of the natural resting aspects for cup-shaped parts.

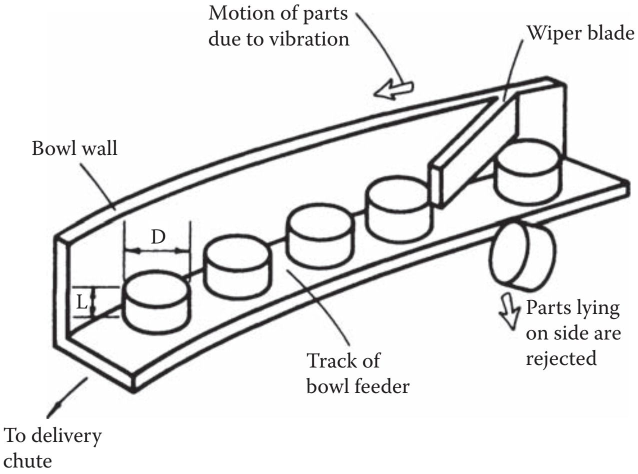

Motion of parts due to vibration
Wiper blade
Bowl wall
D
L
Parts lying on side are rejected
Track of bowl feeder
To delivery chute

FIGURE 3.43 Simple orienting system for a vibratory-bowl feeder ($L/D = 0.7$).

Figure 3.43 shows another orienting system for a vibratory-bowl feeder. The parts being fed and oriented are cylinders whose L/D ratio is 0.7. The wiper blade is adjusted to reject parts lying on their sides and to allow parts lying on end to pass to the delivery chute. Clearly, the feed rate of oriented parts depends on the rate at which the parts encounter the wiper blade and the proportion of these parts that are lying on end. For the case shown in Figure 3.43, the proportion of parts lying on end is, surprisingly, only about 0.3. This means that only 30% of parts fed to the wiper blade will pass through to the delivery chute.

From the preceding example, it is seen once again that knowledge of the probabilities of the various ways the part will naturally rest (natural resting aspects) is essential in any analysis of the performance of the orienting system. In some cases, it is also necessary to know how a particular natural resting aspect will separate into various orientations on the bowl track. The difference between natural resting aspect and orientation is illustrated in Figure 3.44. Here, both parts have the same natural resting aspect (that is, lying on their large faces) but have different orientations on the bowl track.

3.17.1 ASSUMPTIONS

Repeated observations and analyses of the behavior of a variety of parts dropped onto different surfaces have led to the following conclusions [9]:

1. Surfaces can be divided into two main categories. First, there is the soft rubber-like type of surface (referred to as *soft surfaces*). On impact, a corner of the part digs into the surface, resulting in an impact force having a significant horizontal component in addition to a vertical component. The actions of these force components and the nature of

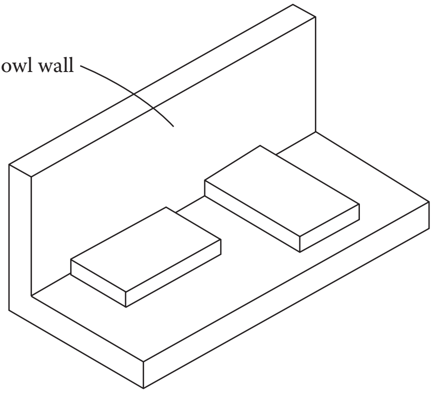


FIGURE 3.44 Rectangular parts on a track.

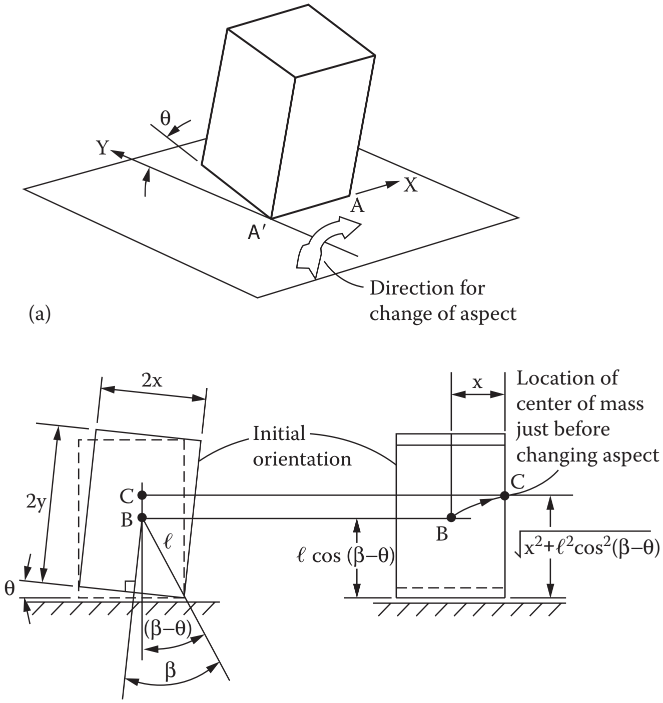
the contact between the part and the surface cause the part to cartwheel across the surface, changing rapidly from one natural resting aspect to another.

The second category of surface is hard and resilient, and includes such materials as metals, glass, and hard laminated plastics. With surfaces of this nature (referred to as *hard surfaces*), the corners of the part do not generally dig into the surface, and the horizontal component of the impact force has a negligible effect. After impact, the part does not usually roll across the surface but bounces up and down, overturning repeatedly, but remaining generally in the same area on the surface. Thus, a change of aspect must be brought about by vertical impact forces applied at the edges and corners of the part.

2. The probability that a part will come to rest in a particular natural resting aspect is a function of two factors: (1) the energy barrier tending to prevent a change of aspect, and (2) the amount of energy possessed by the part when it begins to fall into that natural resting aspect.
3. It will be assumed throughout that parts are dropped from a height sufficient to ensure that, after impact, at least one change in natural resting aspect occurs.

3.17.2 Analysis for Soft Surfaces

Consider a square prismatic part initially resting on a flat horizontal surface, with one of its corners, say A, at the origin of a rectangular XY coordinate system, which also lies on the surface. Figure 3.45 shows this part rotated about the X axis through some angle θ that is small enough to ensure that, if the part possessed no kinetic energy, it would fall onto its end. To move onto its side by rolling over corner A, such that the part rotates about a line parallel to the Y axis, the part, just about to change its aspect, would require sufficient energy to raise its center of mass from the initial position B to position C.


θ
Y
X
A
A′
Direction for change of aspect
(a)
2x
2y
θ
C
B
ℓ
(β–θ)
β
Initial orientation
ℓ cos (β–θ)
x
Location of center of mass just before changing aspect
C
B
$\sqrt{x^2+\ell^2\cos^2(\beta-\theta)}$

(b) View in direction of arrow x

(c) View in direction of arrow y

FIGURE 3.45 Energy required to change aspect of square prism tilted at an angle θ. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

From the projections in Figure 3.45, it can be seen that this change of height is equal to

$$BC = [x^2 + \ell^2 \cos^2 (\beta - \theta)]^{1/2} - \ell \cos (\beta - \theta) \qquad (3.37)$$

where ℓ is given by $(x^2 + y^2)^{1/2}$ and β by arctan (x/y). This expression gives the length of the vertical line *BC* in Figure 3.45b, which is the projection of points *B* and *C* in Figure 3.45c onto a line perpendicular to the *XY* plane. If all such lines (as θ varies from –β to + β) were drawn on the projection in Figure 3.45b, the shaded area shown in Figure 3.46a would result. This shaded area represents the total energy barrier for the part resting on end.

The size of the area can be obtained by integrating Equation 3.37 between the limits θ = ±β. Alternatively, the area can be obtained from Figure 3.46 by geometry.

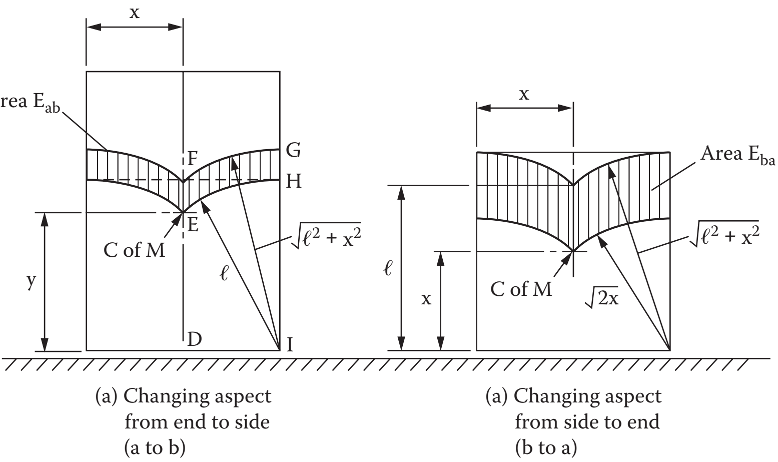


FIGURE 3.46 Energy barriers for a square prism. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

The present theory is based on the hypothesis that the probability that a part will come to rest in a particular orientation is proportional to the area of the energy barrier. This is illustrated in Figure 3.47, which represents the energy

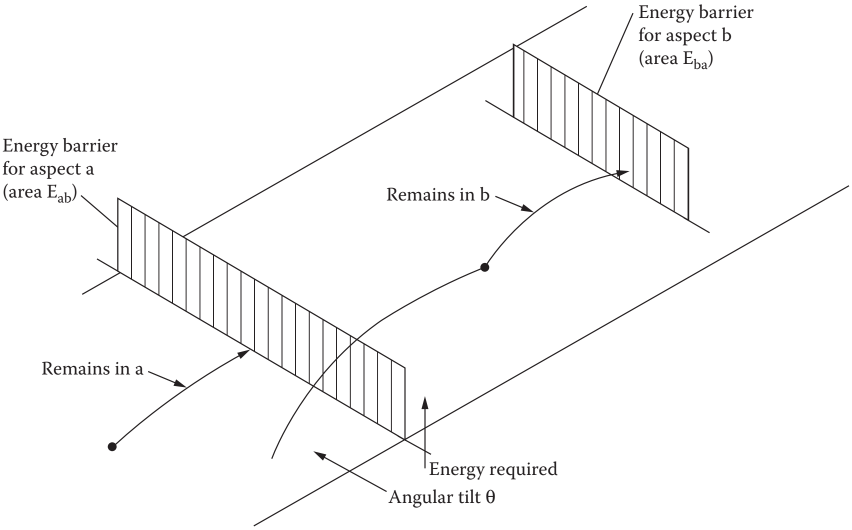

Energy barrier for aspect b (area E_{ba})
Energy barrier for aspect a (area E_{ab})
Remains in b
Remains in a
Energy required
Angular tilt θ

FIGURE 3.47 Representation of energy barriers showing that the number of parts remaining in an aspect will be proportional to the energy barrier for that aspect. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

barriers for a part with only two resting aspects (say, a regular prism or cylinder that can rest only on its side or on end). As the part tumbles end over end, it will encounter, on each change of aspect, the appropriate energy barrier. If it is assumed that as the part passes through each aspect, the probability that it possesses a given amount of kinetic energy is independent of the angle of tilt, then the probability that the part will not surmount the energy barrier will be proportional to the area of the barrier.

Thus, referring to Figure 3.47, the number of parts changing aspect from *a* to *b* that will be stopped by the first energy barrier will be proportional to the area of the energy barrier E_{ab}. Similarly, the number stopped by the second energy barrier will be proportional to E_{ba}. This situation will continue until the part comes to rest.

Thus, in the end, the number of parts N_a and N_b remaining in aspects *a* and *b* will be given, respectively, by

$$N_a = E_{ab} \tag{3.38}$$

$$N_b = E_{ba}$$

Hence, returning to the example in Figure 3.46, by geometry,

$$E_{ab} = 2 \text{ (area enclosed by points } EFGH\text{)} \tag{3.39a}$$

or

$$E_{ab} = 2(A_{DFI} + A_{IFG} - A_{DEI} - A_{IEH}) \tag{3.39b}$$

where A_{DFI} refers to the area enclosed by points *D, F, I;* A_{IFG} refers to the area enclosed by points *I, F, G;* and so on.

Thus, it can be shown that

$$E_{ab} = x^2 \square\square \left(\alpha_2 p^2 + q - \alpha_1 q^2 - \frac{y}{x} \right) \tag{3.40}$$

where

$$p = \frac{(\ell^2 + x^2)^{1/2}}{x} = \left[2 + \left(\frac{y}{x} \right)^2 \right]^{1/2}$$

$$q = \frac{\ell}{x} = \left[1 + \left(\frac{y}{x} \right)^2 \right]^{1/2}$$

$$\alpha_1 = \arcsin \left(\frac{1}{q} \right)$$

$$\alpha_2 = \arcsin \left(\frac{1}{p} \right)$$

$$E_{ba} = x^2 \square\square \left(\alpha x^2 p^2 + q - \frac{\pi}{2} - 1 \right) \tag{3.41}$$

Because the part has two ends and four sides, the probability for aspect *a* (on end) is

$$P_a = \frac{2E_{ab}}{2E_{ab} + 4E_{ba}} \tag{3.42}$$

and the probability for aspect *b* (on the side) is

$$P_b = 1 - P_a \tag{3.43}$$

Calculation of the values of E_{ab} and E_{ba} from Equation 3.40 and Equation 3.41, and substitution in Equation 3.42 and Equation 3.43 give the curve shown in Figure 3.48. Also shown in this figure are the experimental results for steel parts dropped onto a rubber-coated (soft) surface.

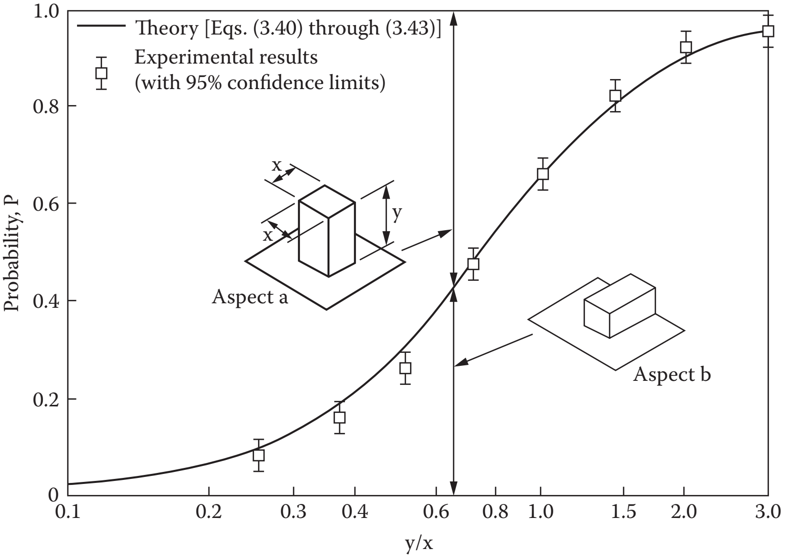


FIGURE 3.48 Probabilities of natural resting aspects for square prisms dropped onto a soft surface. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

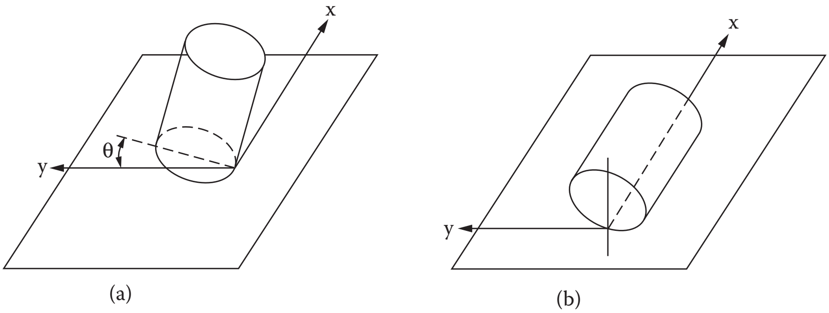
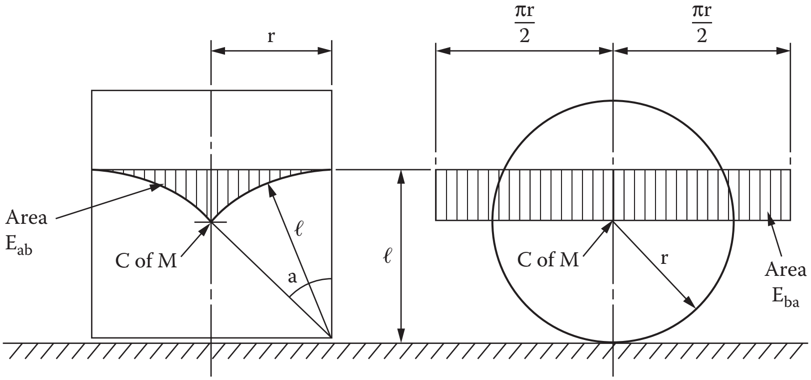


FIGURE 3.49 (a) Solid cylindrical part tilted through an angle θ and (b) solid cylindrical part lying on its side.

The energy barrier for a solid cylindrical part is obtained in a similar manner. Figure 3.49a shows such a part that was initially resting on end on a flat horizontal surface but has been rotated about the *X* axis through a small angle θ so that it would fall onto its end if it were released. To move the cylinder onto its side by now rotating it about the *Y* axis causes the center of mass to rise further, as shown by the energy barrier in Figure 3.50a.

If the part were first lying on its side, as shown in Figure 3.49b, and then rolled on the horizontal surface, the distance from the center of mass to the surface would remain constant. If the part were now rotated onto one end about one of its edges, the energy barrier becomes that shown in Figure 3.50b.



(a) Changing aspect from end to side (a to b)

(b) Changing aspect from side to end (b to a)

FIGURE 3.50 Energy barriers for a cylinder on a soft surface. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

In these cases, the expressions for the areas of the energy barriers are simpler than in the case of a square prism, and

$$E_{ab} = \ell^2[(2 - \cos\alpha)\sin\alpha - \alpha] \tag{3.44}$$

$$E_{ba} = \ell^2(1 - \sin\alpha)\,\pi\sin\alpha \tag{3.45}$$

where $\alpha = \cot(L/D)$ and L is the length and D the diameter of the part. Hence,

$$\begin{aligned} P_a &= \frac{E_{ab}}{E_{ab} + E_{ba}} \\ &= \frac{(2 - \cos\alpha) - (\alpha/\sin\alpha)}{(2 - \cos\alpha) - (\alpha/\sin\alpha) + \pi(1 - \sin\alpha)} \end{aligned} \tag{3.46}$$

and

$$P_b = 1 - P_a \tag{3.47}$$

Rather surprisingly, it is found that, if the results for a square prism (Figure 3.48) are plotted in terms of the L/D ratio of the circumscribed cylinder, they can be very closely approximated by the results in Figure 3.51 for a solid cylinder. Indeed, application of the theory to prisms of any regular cross section (triangular, square, pentagonal, hexagonal, etc.), together with experiments, shows that Equation 3.44 to Equation 3.47 apply to any solid regular prism, where L/D is defined as the length-to-diameter ratio of the circumscribed cylinder. This is illustrated in Figure 3.52.

3.17.3 ANALYSIS FOR HARD SURFACES

For hard surfaces, the approach described by Boothroyd et al. [10] can be used in conjunction with the new energy-barrier technique described above. In this case, it is assumed that an extra amount of energy is required to change the aspect of a part because energy can be provided only by a vertical impact force applied at one of the edges or corners of the part. In addition, allowance must be made for the effect of this additional energy, which tends to keep the part from remaining in the new aspect.

Again, as with the soft-surface solution and experiments, it was found that the results for a solid cylinder could be applied to any prism of regular cross section, with three or more sides, that could be enclosed within the cylinder.

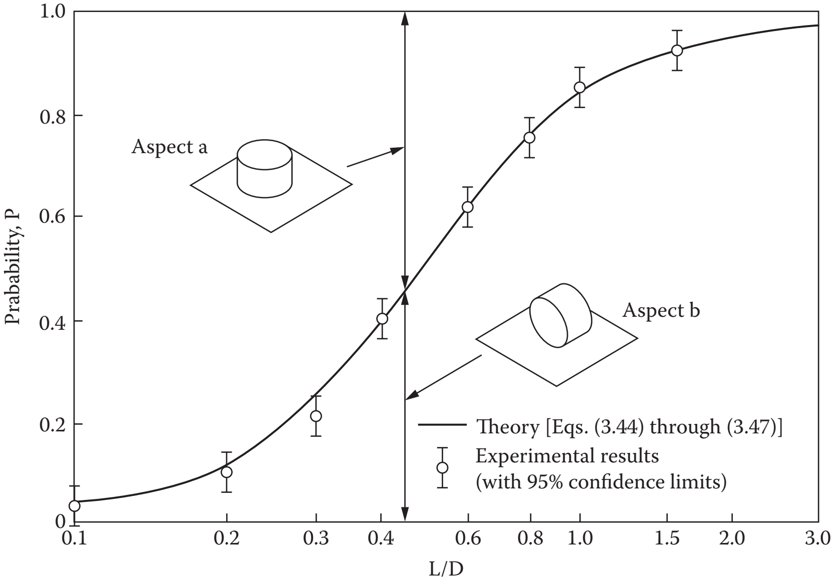


FIGURE 3.51 Probabilities of natural resting aspects for cylinders dropped onto a soft surface. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

3.17.4 Analysis for Cylinders and Prisms with Displaced Centers of Mass

If the center of mass of a cylinder is displaced along its axis from the midpoint, the probabilities that the cylinder will come to rest on either of its ends become different. Based on experimental and theoretical work, it was found that the approach described earlier for both hard and soft surfaces could be applied equally successfully to this problem.

3.17.5 Summary of Results

Figure 3.53 presents a complete summary of the results of this work. It can be seen that the probabilities for the natural resting aspects of all prisms of regular cross section can be presented in just two graphs: one for a soft surface and one for a hard surface.

3.18 ANALYSIS OF A TYPICAL ORIENTING SYSTEM

In general, an orienting system for a vibratory-bowl feeder consists of one or more orienting devices arranged in series along the bowl track. These devices

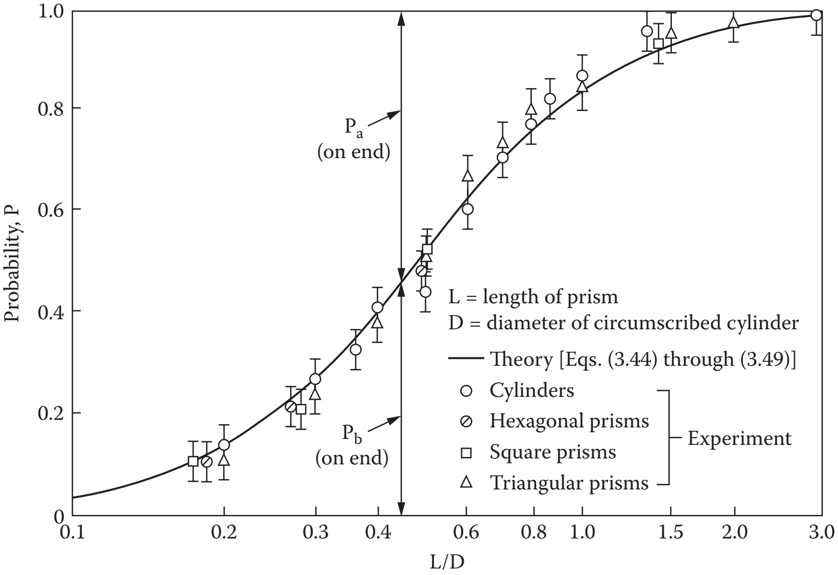


FIGURE 3.52 Probabilities of natural resting aspects for cylinders and various regular prisms dropped onto a soft surface. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

are usually located near the outlet of the feeder along a horizontal portion of the track. Because the track section is level, the parts can travel at a conveying velocity that is greater than the velocity of the parts on the preceding incline, thus enabling parts to separate and eliminating interference between adjacent parts as they pass the various devices. Such a system is shown in Figure 3.54 for the feeding and orienting of right rectangular prisms. The six orientations for these prisms are also described in this figure.

The first device is a wiper blade, and it rejects orientations *c, d, e,* and *f* back into the bowl. It also serves to remove the secondary layers of parts, where one part rests on another instead of on the track. The output of this device is in either *a* or *b* orientation.

The narrow track is next, and it rejects orientation *b* back into the bowl, leaving only orientation *a*. The riser turns orientation *a* into orientation *c,* which is the output orientation of the system.

The matrices for these devices and systems are:

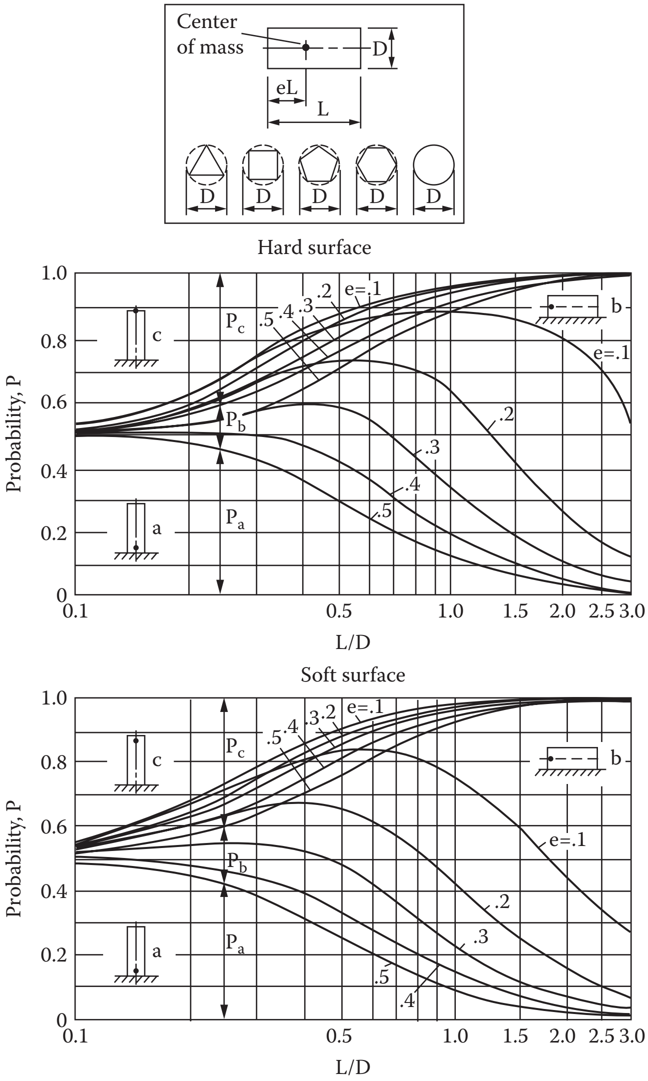


FIGURE 3.53 Probabilities of natural resting aspects for prisms of regular cross section; *L* is the length of prism and *D* the diameter of circumscribed cylinder. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

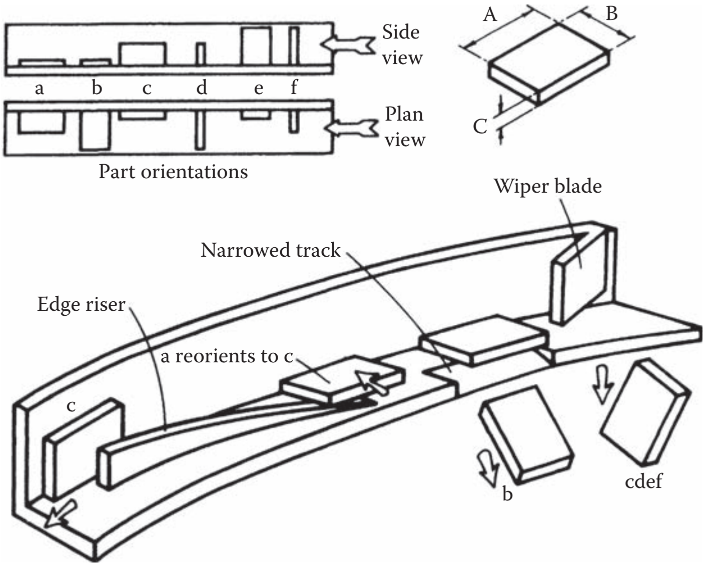


FIGURE 3.54 Orienting system for right rectangular prisms.

$$\begin{array}{ccccccc}
\textbf{Wiper blade} & & \textbf{Narrow track} & & \textbf{Riser} & & \textbf{System} \\
\begin{array}{cc} & \begin{matrix} a & b \end{matrix} \\ \begin{matrix} a\\ b\\ c\\ d\\ e\\ f \end{matrix} & \begin{bmatrix} 1 & 0\\ 0 & 1\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0 \end{bmatrix} \end{array}
& &
\begin{array}{cc} & a \\ \begin{matrix} a\\ b \end{matrix} & \begin{bmatrix} 1\\ 0 \end{bmatrix} \end{array}
& &
\begin{array}{cc} & c \\ a & \begin{bmatrix} 1 \end{bmatrix} \end{array}
& = &
\begin{array}{cc} & c \\ \begin{matrix} a\\ b\\ c\\ d\\ e\\ f \end{matrix} & \begin{bmatrix} 1\\ 0\\ 0\\ 0\\ 0\\ 0 \end{bmatrix} \end{array}
\end{array}$$

Rectangular prisms, when tossed onto a horizontal surface, can come to rest on one of three pairs of faces. These positions are the three natural resting aspects for these parts. The probabilities for a prism coming to rest in these three aspects are shown in Figure 3.55. The dimensions of the parts used in this particular system are 45mm × 30mm × 3 mm. The values c/s and c/b are 0.07 and 0.10, respectively. According to Figure 3.55, virtually all these parts will rest on their largest face when tossed onto a hard horizontal surface, such as the bottom of a bowl feeder. However, within this one natural resting aspect, there are two

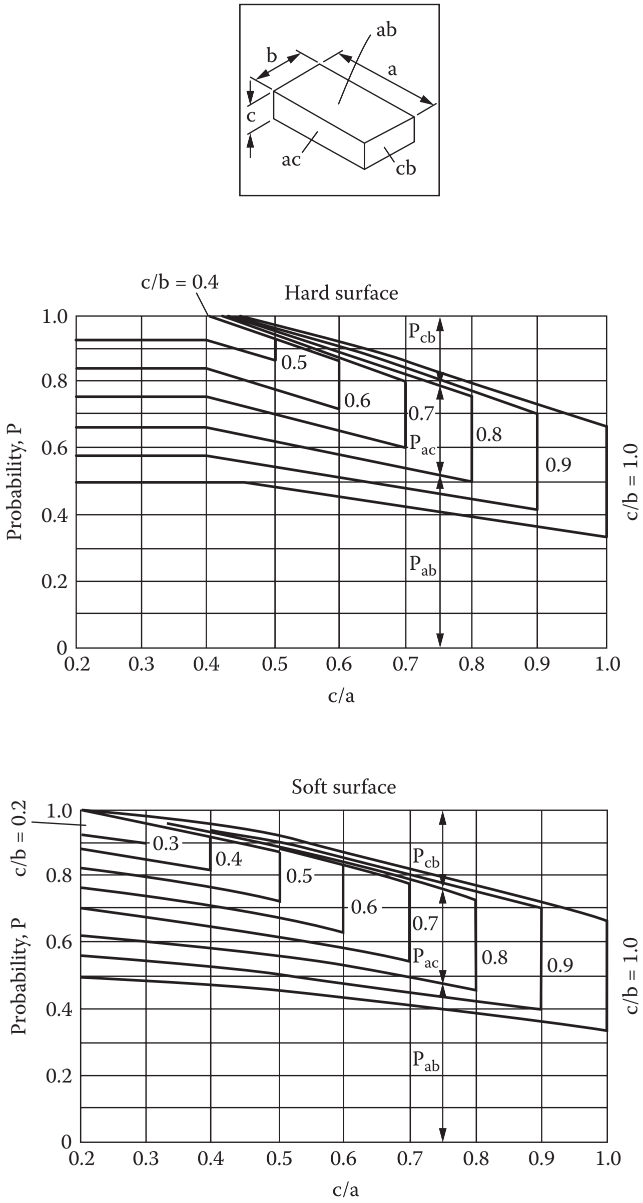


FIGURE 3.55 Probabilities of natural resting aspects for right rectangular prisms. (From Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997. With permission.)

possible orientations (*a* and *b*). Parts in the bottom of the bowl tend to rotate into one of these orientations before they travel up the inclined track. For aluminum parts on a steel track, the coefficient of friction μ is 0.4. Thus, from Ho and Boothroyd [12], or Figure 3.56, it can be seen that, for these parts, the partition ratio $R = P_a/(P_a + P_b)$ is 0.63 and, therefore, the probabilities are given by

$$P_a = R(P_a + P_b) = 0.63, \; P_b = 0.37$$

The initial distribution matrix (IDM) showing the probable distribution of the various orientations is, therefore,

$$\begin{array}{cccccc} a & b & c & d & e & f \\ [0.63 & 0.37 & 0 & 0 & 0 & 0] \end{array}$$

Thus, the efficiency η of this system, which is given by the product of the IDM and the system matrix, is 63%.

The average length of a part entering this system is the product of the IDM and a matrix of the lengths of the part in the corresponding orientations in the conveying direction. For these parts, the average part length $\bar{\ell}$ is

$$[0.63 \quad 0.37 \quad 0 \quad 0 \quad 0 \quad 0] \begin{bmatrix} 45 \\ 30 \\ 45 \\ \text{[illegible]} \\ 30 \\ \text{[illegible]} \end{bmatrix} = 39\text{[illegible]} \text{ mm}$$

The feed rate F can be found from

$$F = \eta \frac{v}{\bar{\ell}} \tag{3.48}$$

where v is the conveying velocity of the parts on the inclined section of the track when adjacent parts are in contact. The feed rate of any system can be found in a similar manner, using the initial distribution matrix, system matrix, length matrix, and Equation 3.48. The feed rate can also be determined from

$$F = vE/A \tag{3.49}$$

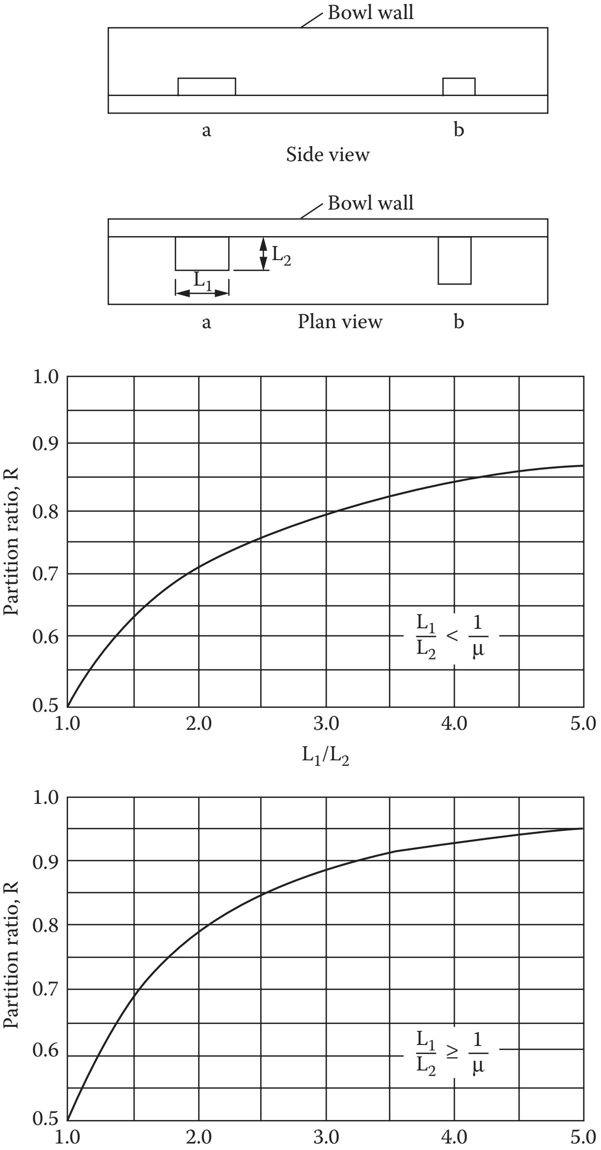


FIGURE 3.56 Probabilities of orientations of rectangular prisms on a bowl-feeder track. P_a is the probability of orientation *a*; P_b is the probability of orientation *b*; partition ratio $R = P_a/(P_a + P_b)$; μ is the coefficient of friction between parts and bowl track; and L_1 and L_2 are the length of long and short sides, respectively, for the part-track interface ($L_1 \geqslant L_2$). (From Ho, C. and Boothroyd, G., Orientation of Parts on the Track of a Vibratory Feeder, *Proceedings of the Fifth North American Metalworking Research Conference*, SME, p. 363, Dearborn, Michigan, 1977. With permission.)

where E is the modified efficiency of the orienting system and is given by

$$E = \eta A / \bar{\ell} \tag{3.50}$$

3.18.1 DESIGN OF ORIENTING DEVICES

To achieve the calculated 63% efficiency, the orienting devices that make up the system must be properly designed. Design data and performance curves for orienting devices used in vibratory-bowl feeders are provided in Appendix D, which is based on the *Handbook of Feeding and Orienting Techniques for Small Parts* [11].

For the wiper blade, which rejects orientations *c, d, e,* and *f* (Figure 3.54), the angle θ between the wiper blade and the bowl wall is set to avoid the jamming action produced by overlapping parts, as shown in Figure 3.57. The smallest jamming angle β_w for these parts is arctan (3/45) or 3.8° (0.07 rad), and the maximum value of θ_w is 18° (0.31 rad). The height of the wiper blade should be 5 mm, which is sufficient to remove a secondary layer of parts.

The narrow-track device rejects orientation *b* but allows orientation *a* to pass. From Figure 3.58 and a conveying velocity of 100 mm/sec, the corresponding

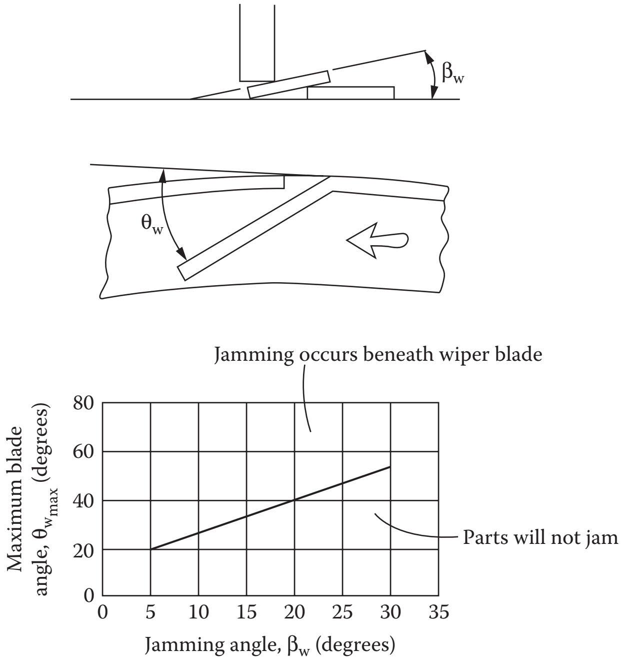

βw
θw
Jamming occurs beneath wiper blade
Maximum blade angle, θwmax (degrees)
80
60
40
20
0
0
5
10
15
20
25
30
35
Jamming angle, βw (degrees)
Parts will not jam

FIGURE 3.57 Wiper blade design.

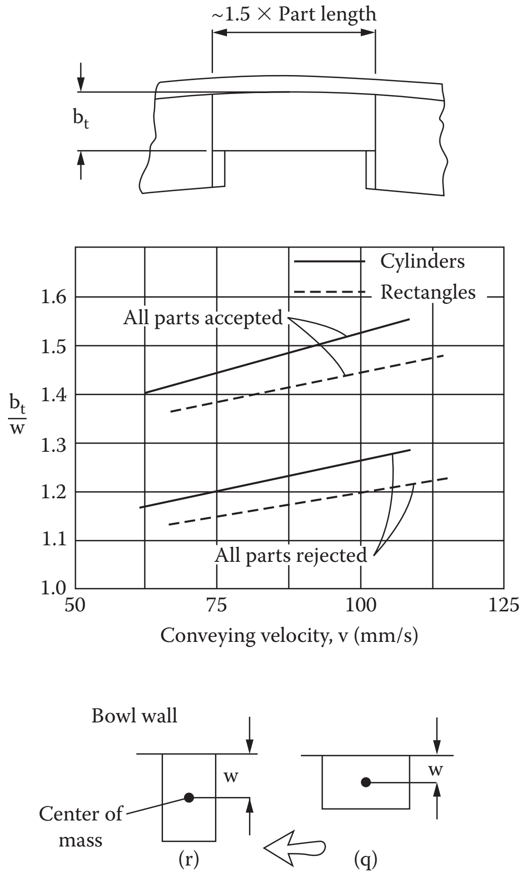


FIGURE 3.58 Narrow-track design.

values for the dimensionless track width b_t/w are 1.2 and 1.45, respectively. Thus, in millimeters,

$$(1.2)\ (22.5) > b_t > (1.45)\ (15)$$

or

$$27 > b_t > 22$$

The narrow track should be 23 mm wide and 67 mm long.

The edge-riser orienting device turns orientation *a* into orientation *c*. The design information for this device is presented in Figure 3.59. For a 6° (0.10-rad) riser angle and parts measuring 45 mm × 30 mm × 3 mm, *B*/*C* equals 10, and the ramp length is 300 mm. Other riser angles and lengths will also produce satisfactory results.

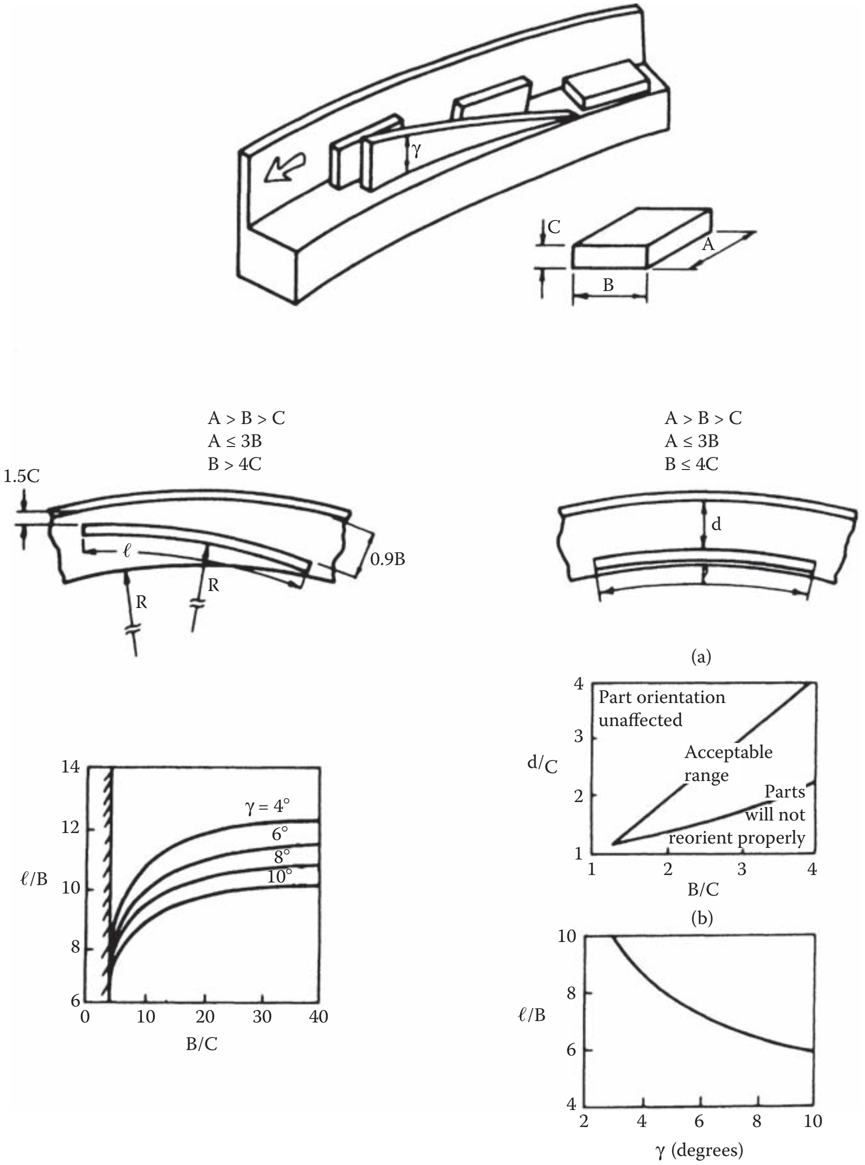


FIGURE 3.59 Design data for the edge-riser orienting device.

3.19 OUT-OF-BOWL TOOLING

A further type of orienting device is that which is situated between the feeder and the workhead. Such devices are usually of the active type because orientation by rejection is not often practicable. Figure 3.60 illustrates a device described by

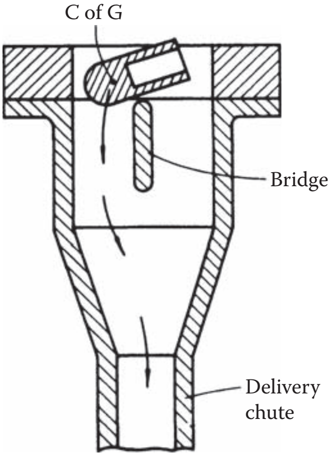


FIGURE 3.60 Reorientation of cup-shaped part (C of G is center of gravity). (From Tipping, W.V., Mechanized Assembly Machines, 9: Orientation and Selection, *Machine Design Engineering,* p. 36, Feb. 1966. With permission.)

Tipping [13] in which the position of the center of gravity of a part is utilized. In this example, the cup-shaped part is pushed onto a bridge, and the weight of the part acting through the center of gravity pulls the part down nose first into the delivery chute. In Figure 3.61, the same part is reoriented using a different

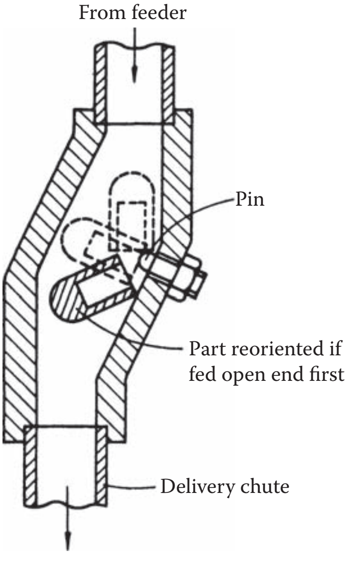


FIGURE 3.61 Reorientation of cup-shaped part. (From Tipping, W.V., Mechanized Assembly Machines, 9: Orientation and Selection, *Machine Design Engineering,* p. 36, Feb. 1966. With permission.)

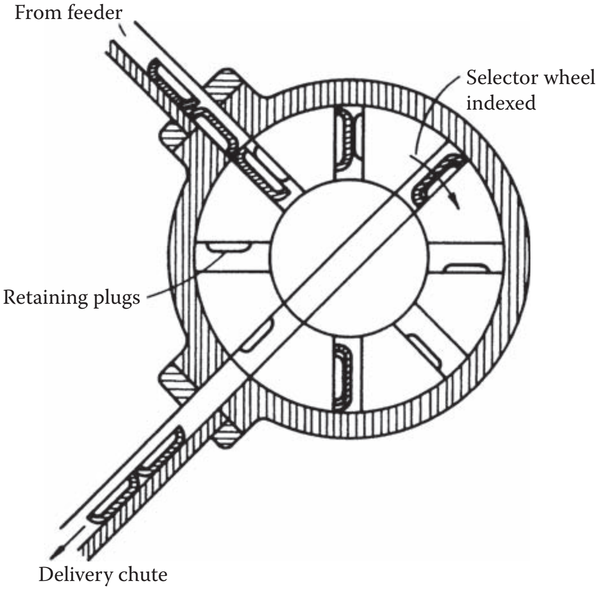


FIGURE 3.62 Reorientation of shallow-drawn parts. (From Hopper Feeds as an Aid to Automation, *Machinery's Yellowback No. 39*, Machinery Publishing, Brighton, England. With permission.)

principle. With this method, if the part passes nose first down the delivery tube, it is deflected directly into the delivery chute and maintains its original orientation. A part fed open end first will be reoriented by the pin located in the wall of the device.

The device illustrated in Figure 3.62 is known as a selector and employs a principle that has been applied successfully to reorient a wide variety of parts [14]. The selector consists of a stationary container in which a wheel with radial slots is mounted. The wheel is driven by an indexing mechanism to ensure that the slots always align with the chutes. In the design illustrated, the shallow-drawn parts may enter the slot in the selector wheel in either of two attitudes. After two indexes, the parts are aligned with the delivery chute and those that now lie open end upward slide out of the selector and into the delivery chute. Those that lie open end downward are retained by a plug in the slot. After a further four indexes, the slot is again aligned with the delivery chute.

REFERENCES

1. Redford, A.H. and Boothroyd, G., Vibratory Feeding, *Proceedings of the Institution of Mechanical Engineers*, Vol. 182, Part 1, No. 6, p. 135, London, 1967–1968.
2. Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Salford University, Salford, England, 1966.

3. Boothroyd, G., Poli, C.R., and Murch, L.E., Feeding and Orienting Techniques for Small Parts, SME Technical Paper AD72–763, 1975.
4. Jimbo, Y., Yokoyama, Y., and Okabe, S., Vibratory Conveying, *Bulletin of the Japan Society of Precision Engineering*, Vol. 4, No. 3, pp. 59–64, 1970.
5. Yokoyama, Y., Okabe, S., Shiozawa, A., and Watanabe, M., The Balanced Vibratory Feeder and Its Application for Automated Assembly System, *Proceedings of the 4th International Conference on Production Engineering*, Tokyo, pp. 907–912, 1980.
6. Murch, L.E. and Boothroyd, G., Design of Orienting Systems for Vibratory-Bowl Feeders, SME Technical Paper FC72–235, 1972.
7. Murch, L.E. and Boothroyd, G., Predicting Efficiency of Parts Orienting Systems, *Automation*, Vol. 18, Feb. 1971.
8. Boothroyd, G. and Murch, L.E., Performance of an Orienting Device Employed in Vibratory-Bowl Feeders, *Transactions of the ASME, Journal of Engineering for Industry*, Aug. 1970.
9. Boothroyd, G. and Ho, C., Natural Resting Aspects of Parts for Automatic Handling, *Transactions of the ASME, Journal of Engineering for Industry*, Vol. 99, pp. 314–317, May 1997.
10. Boothroyd, G., Redford, A.H., Poli, C., and Murch, L.E., Statistical Distribution of Natural Resting Aspects of Parts for Automatic Handling, *Manufacturing Engineering Transactions*, Vol. 1, 1972.
11. Boothroyd, G., Poli, C., and Murch, L.E., *Handbook of Feeding and Orienting Techniques for Small Parts,* University of Massachusetts, Amherst, MA, 1977.
12. Ho, C. and Boothroyd, G., Orientation of Parts on the Track of a Vibratory Feeder, *Proceedings of the Fifth North American Metalworking Research Conference,* SME, p. 363, Dearborn, MI, 1977.
13. Tipping, W.V., Mechanized Assembly Machines, 9: Orientation and Selection, *Machine Design Engineering,* p. 36, Feb. 1966.
14. Hopper Feeds as an Aid to Automation, *Machinery's Yellowback No. 39*, Machinery Publishing, Brighton, England.

4 Automatic Feeding and Orienting — Mechanical Feeders

Although the vibratory-bowl feeder is the most widely employed and most versatile parts-feeding device, many other types of parts feeders are available. Usually, these are suitable only for feeding certain basic types of component parts but better results may be obtained for a smaller capital outlay with feeders other than the vibratory type.

One point that must be borne in mind when we consider parts feeders is that, in automatic assembly, the output of parts from the feeder is always restricted by the machine being fed. The machine generally uses parts at a strictly uniform rate, which may be referred to as the *machine rate*. In the design and testing of parts feeders, it is often convenient to observe the feed rate when the feeder is not connected to a machine, that is, when no restriction is applied to the output of the feeder. The feed rate under these circumstances will be referred to as the *unrestricted feed rate*. Clearly, in practice, the mean unrestricted feed rate must not fall below the machine rate.

Certain other general requirements of parts feeders may be summarized as follows: The unrestricted feed rate should not vary widely, because this simply means that when the feeder is connected to a machine, the parts are continuously recirculated within the feeder for much of the time. This causes excessive wear and may eventually damage the parts. This undesirable characteristic often occurs in parts feeders in which the feed rate is sensitive to changes in the quantity of parts present in the feeder and will be referred to as the *load sensitivity* of the feeder.

With parts feeders suitable for automatic machines, it is necessary that all the parts be presented to the machine in the same orientation; that is, they must be fed correctly oriented. Some feeders are able to feed and orient many types of parts, whereas others are able to handle only a very limited range of part shapes.

Undoubtedly, the reliability of a parts feeder is one of its most important characteristics. Parts feeders should be designed so that the possibility of parts jamming in the feeder, or in its orienting devices, is minimized or eliminated.

It is sometimes suggested that parts feeders can also act as inspection devices. It is possible to design certain parts feeders so that misshapen parts, swarf, and so on, will not be fed to the machine but will be rejected by the device fitted to the feeder. This can be an important feature because defective parts or foreign matter, if fed to the machine, will probably cause a breakdown and may stop the whole production line.

Some parts feeders are noisy in operation, and some tend to damage certain types of parts. Obviously, both these aspects of parts feeding must be considered when studying the possible alternatives for a particular application.

Parts feeders can generally be classified into the following: reciprocating feeders, rotary feeders, belt feeders, and vibratory feeders, which were discussed in Chapter 3. A selection of the more common feeding devices within each of these groups will now be described and discussed.

4.1 RECIPROCATING-TUBE HOPPER FEEDER

A reciprocating-tube hopper is illustrated in Figure 4.1 and consists of a conical hopper with a hole in the center, through which a delivery tube passes. Relative vertical motion between the hopper and the tube is achieved by reciprocating either the tube or the hopper. During the period when the top of the tube is below the level of parts, some parts will fall into the delivery tube. It is usual to machine the top of the tube at an angle such that a part resting across the opening will fall clear and not block the opening as the tube is pushed upward through the mass of parts. Care must be taken in choosing the angle of the conical hopper because, if the angle is too small, parts may jam between the tube and the hopper.

Figure 4.2 shows the forces acting on a cylindrical part jammed in this way when the tube is moving downward relative to the hopper. The force W acting vertically downward represents the weight of the part, together with any additional force that may be present as a result of parts resting on top of the one shown. Resolving forces vertically and horizontally and taking moments about A gives

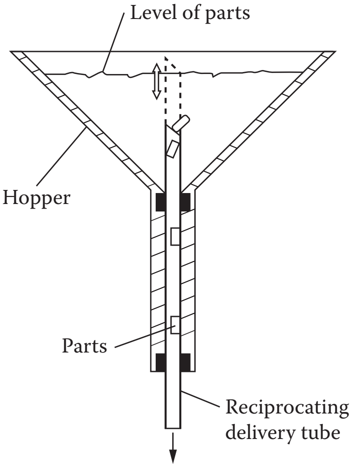


FIGURE 4.1 Reciprocating-tube hopper.

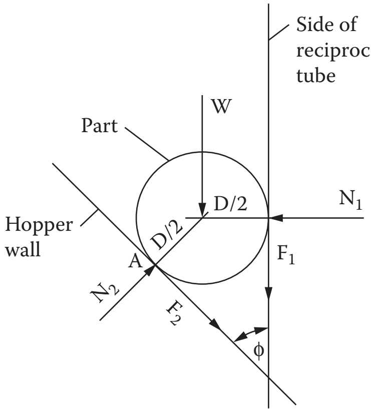


FIGURE 4.2 Forces acting on a part jammed between the hopper wall and the tube.

$$F_1 + W + F_2 \cos \phi = N_2 \sin \phi \tag{4.1}$$

$$N_1 = N_2 \cos \phi + F_2 \sin \phi \tag{4.2}$$

$$F_1 \,(1 + \cos \phi)\, D/2 + W(D/2) \cos \phi = N_1 \,(D/2) \sin \phi \tag{4.3}$$

where φ is the hopper wall angle, and D the diameter of the part.

Eliminating W from Equation 4.1 and Equation 4.3 gives, after rearrangement,

$$\begin{aligned} N_1 \sin \phi = F_1 \,(1 + \cos \phi) + \cos \phi \\ \times (N_2 \sin \phi - F_2 \cos \phi - F_1) \end{aligned} \tag{4.4}$$

The maximum value of F_2 is given by $\mu_s N_2$ (where μ_s is the coefficient of static friction) and, thus, writing $F_2 = \mu_s N_2$ in Equation 4.2 and Equation 4.4 and eliminating N_2 give

$$\frac{F_1}{N_1} = \frac{\mu_s}{\cos \phi + \mu_s \sin \phi} \tag{4.5}$$

For the tube to slide, $F_1/N_1 > \mu_s$, and, therefore, from Equation 4.5,

$$\frac{1}{\cos \phi + \mu_s \sin \phi} > 1 \tag{4.6}$$

The expression indicates that the value of φ should be as large as possible to prevent jamming when μ_s is large. However, when $\mu_s < \cot \phi$, the parts cannot slide down the hopper wall. The best compromise is probably given by writing the following two limiting conditions:

$$\mu_s = \cot \phi \tag{4.7}$$

$$\cos \phi + \mu_s \sin \phi = 1 \tag{4.8}$$

Combining Equation 4.7 and Equation 4.8 gives $\phi = 60°$ and, on substitution of this value in expression 4.6, it is found that, to prevent jamming under these conditions, the coefficient for friction μ_s must be less than 0.577. Because this value is greater than that expected in practice, it may be concluded that, with a hopper angle of 45°, the possibility of jamming will generally be avoided if the coefficient of friction is less than 0.414.

4.1.1 General Features

The optimum hopper load is that which fills half the volume of the hopper, and the delivery tube should rise just above the maximum level of parts in the hopper. The inside silhouette of the delivery tube must be designed to accept only correctly oriented parts one at a time. The linear velocity of the delivery tube should be no greater than 0.6 m/sec.

4.1.2 Specific Applications

Figure 4.3 shows some specific results for the feeding of cylinders adapted from the *Handbook of Feeding and Orienting Techniques for Small Parts* [1], which is presented in Appendix D. From the figure it is possible to estimate the feed rates obtainable for a range of cylindrical parts.

4.2 CENTERBOARD HOPPER FEEDER

Figure 4.4 shows a typical centerboard hopper feeder. Basically, this consists of a hopper, in which the parts are placed at random, and a blade with a shaped track along its upper edge, which is periodically pushed upward through the mass of parts. The blade will thus catch a few parts on its track during each cycle; when the blade is in its highest position (as shown in the figure), it is aligned with a chute, and the parts will slide down the track and into the chute. The centerboard hopper illustrated is suitable for feeding cylindrical parts.

4.2.1 Maximum Track Inclination

One of the important parameters in a centerboard hopper design is the angle of inclination of the track when the blade is in its highest position (θ_m in Figure 4.4). It is assumed, for the purposes of the following analysis, that the cam drive is arranged such that the blade is lifted rapidly to its highest position, allowed to

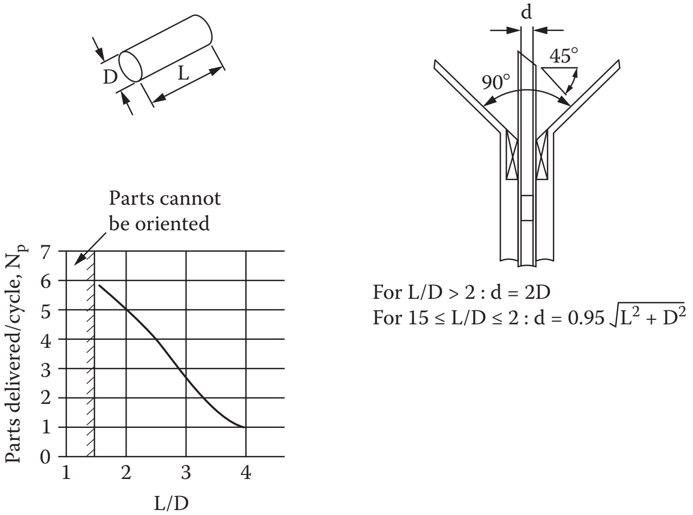


FIGURE 4.3 Performances of a reciprocating-tube hopper when feeding cylindrical parts.

dwell for a period while the parts slide into the chute, and then rapidly returned to its lowest position when the track is horizontal and aligned with the bottom of the hopper.

Clearly, there is a limit on the deceleration of the blade on its upward stroke; otherwise, the parts leave the track and are thrown clear of the feeder. Thus, for a given deceleration, an increase in the angle θ_m increases the time taken for the blade to complete its upward motion. However, with larger values of θ_m, the time taken for the parts to slide off the track is less and, when θ_m is chosen to give maximum frequency of reciprocation and hence maximum feed rate, a compromise must be sought.

The tendency for a part to leave the track during the upward motion of the blade is greatest at the end of the track farthest away from the pivot. The forces acting on a part in this position are shown in Figure 4.5 and, from the figure, the condition for the reaction between the part and the track to become zero is given by

$$m_p \alpha \left(r_b - \frac{L}{2} \right) = -m_p g \cos \theta_m \tag{4.9}$$

where L is the length of the part, m_p the mass of the part, r_b the radius from the pivot to the upper end of the track, θ_m the maximum angle between the track and the horizontal, and α the angular acceleration of the track.

Thus, the maximum angular deceleration of the blade is approximately given by

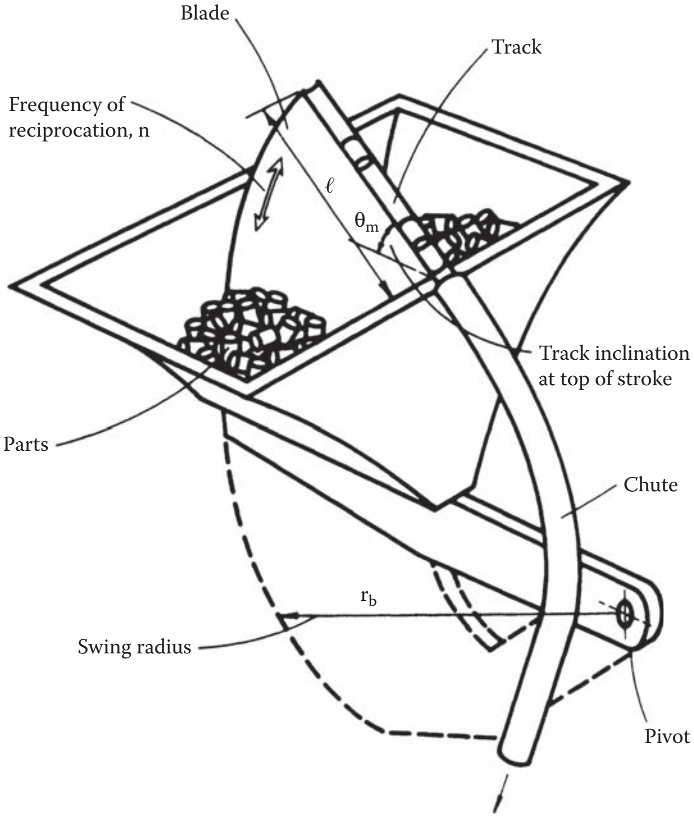

Blade
Track
Frequency of reciprocation, n
ℓ
θm
Track inclination at top of stroke
Parts
Chute
rb
Swing radius
Pivot

FIGURE 4.4 Centerboard hopper feeder.

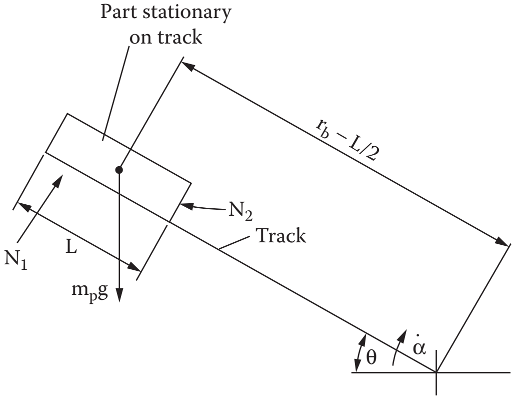


FIGURE 4.5 Forces acting on a part during the upward motion of the blade.

$$-\alpha = \frac{g}{r_b}\cos\theta_m \tag{4.10}$$

if L is small compared with r_b.

For simplicity, it is now assumed that, during the period of the upward motion of the blade, the drive to the blade is designed to give (1) a constant acceleration of $(g \cos \theta_m)/r_b$ followed by (2) a constant deceleration of $(g \cos \theta_m)/r_b$. Under these conditions, the total time t_1 taken to lift the blade so that the track is inclined at an angle θ_m to the horizontal is given by

$$t_1^2 = \frac{4r_b\theta_m}{g\cos\theta_m} \tag{4.11}$$

It is now assumed that when the blade is in its highest position, it dwells for a period t_2, just long enough to allow the parts to slide down the track. This is given, in the worst case, by the time taken for one part to slide the whole length of the track. The forces acting on a part under these circumstances are shown in Figure 4.6, and resolving in a direction parallel to the track gives

$$m_p a = m_p g \sin \theta_m - \mu_d m_p g \cos \theta_m \tag{4.12}$$

where a is the linear acceleration of the part down the track, and μ_d is the coefficient of dynamic friction between the part and the track. The minimum dwell period t_2 is now given by

$$t_2^2 = \frac{2\ell}{g(\sin \theta_m - \mu_d \cos \theta_m)} \tag{4.13}$$

where ℓ is the total length of the track.

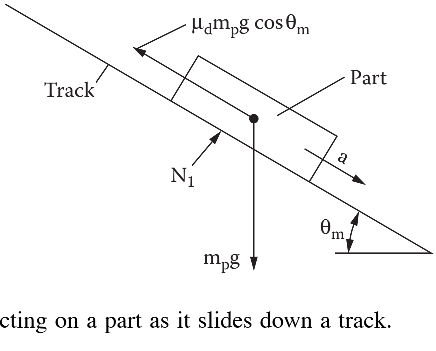


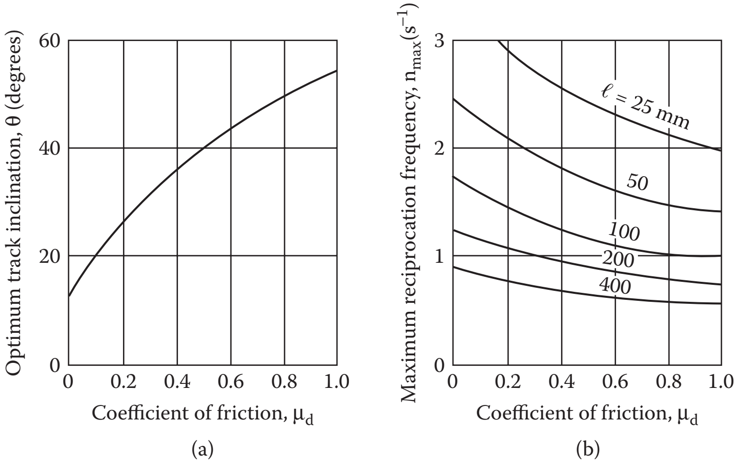
FIGURE 4.6 Forces acting on a part as it slides down a track.

If the time taken to return the blade to its lowest position is now assumed to be the same as the time for the up stroke, then the total period t_f of the feeder cycle is given by

$$t_f = 2t_1 + t_2 = 2\left(\frac{4r_b\theta_m}{g\cos\theta_m}\right)^{1/2} + \left[\frac{2\ell}{g(\sin\theta_m - \mu_d\cos\theta_m)}\right]^{1/2} \tag{4.14}$$

Equation 4.14 consists of two terms; one that increases as θ_m is increased and one that decreases as θ_m is increased. An optimum value of θ_m always exists that gives the minimum period t_f and, hence, a maximum theoretical feed rate. It can be shown mathematically that this optimum value of θ_m is a function only of μ_d and the ratio r_b/ℓ. However, the resulting expression is unmanageable, but the curve shown in Figure 4.7a gives the solution for a practical value of r_b/ℓ of 2.0. For example, with a coefficient of dynamic friction of 0.4, the optimum track angle would be approximately 36°.

Figure 4.7b shows how the maximum frequency of the blade cycle $n_{\max}$ (given by $1/t_f$) varies as the coefficient of friction between part and track is changed and when the ratio r_b/ℓ is 2.0. It can be seen that, for large values of μ_d in the range 0.4–0.8, the maximum blade frequency varies by only 10–15%. The maximum blade frequency is more sensitive to changes in the length ℓ of the track and, for longer tracks, the frequency is lower. However, it should be remembered that,



(a) (b)

FIGURE 4.7 Characteristics of centerboard hopper (r_b/ℓ = 2.0).

for a given size of a part, a longer track, on average, picks up a greater number of parts per cycle and, hence, the mean feed rate may increase.

The maximum number of parts that may be selected during each cycle is given by ℓ/L. In practice, the average number selected is less than this and, if E is taken to be the efficiency of a particular design, the average number of parts fed during each cycle is given $E\ell/L$, and the mean feed rate F of the hopper feeder is given by

$$F = \frac{nE\ell}{L} \tag{4.15}$$

where the blade frequency n is given by

$$n = \frac{1}{t_f} \tag{4.16}$$

In practice, the values of efficiency E must be obtained from experiments.

4.2.2 LOAD SENSITIVITY AND EFFICIENCY

For a centerboard hopper feeder working at a constant frequency, any variation in feed rate as the hopper gradually empties will be due to changes in the efficiency E. This has been defined as the ratio between the average number of parts selected during one cycle and the maximum number that can be selected. Figure 4.8 and Figure 4.9 show the results of tests on an experimental feeder in which $\ell/L = 6$, $r_b/\ell = 2$, and $\theta_m = 54°$. The lower curve in Figure 4.8 shows how the efficiency E varied as the hopper gradually emptied, and it is interesting to note that a rapid increase in E occurs when less than 100 parts remain in the hopper. The upper curve in Figure 4.8 shows that this high efficiency can be maintained for all hopper loadings if a baffle is placed on one side of the hopper blade. The baffle would therefore appear to affect the orientation of those parts likely to be selected by the blade. Clearly, the load-sensitivity characteristics obtained with this latter design approach the ideal situation very closely. Each of the experimental points in Figure 4.8 represents the average of 80 results. In Figure 4.9, one set of 80 results (for a hopper load of 200 parts) is plotted in the form of a histogram and exhibits the familiar normal distribution. The average number of parts selected in this case was 3.2 and, because the maximum number of parts that could be selected by the blade was 6, this represents an efficiency of 0.53.

Figure 4.10 illustrates a specific application for the centerboard hopper feeder. In the figure, the effect of part proportions on the efficiency E is presented, which allows an estimate of the feed rate to be made.

A final design consideration is the inclination of the sloping sides of the hopper. If the inclination is too great, there is a possibility that parts will jam

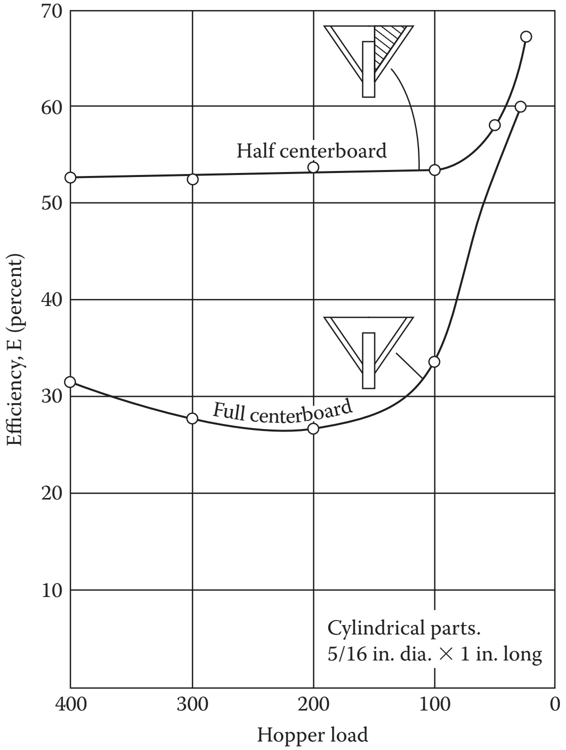


FIGURE 4.8 Load sensitivity of a centerboard hopper.

between the hopper wall and the blade when the blade is moving downward. This situation is identical to that of the reciprocating-tube hopper, and the analysis indicated that the included angle between the hopper wall and the blade should be 60°.

4.3 RECIPROCATING-FORK HOPPER FEEDER

A reciprocating-fork hopper, shown in Figure 4.11, is suitable only for feeding headed parts. It consists of a shallow cylindrical bowl that rotates about an axis inclined at approximately 10° to the vertical and a fork that reciprocates in the vertical plane about point *A*. In its lowest position, the fork is horizontal, and rotation of the bowl causes parts to be caught in the fork. The fork then lifts a few parts by their heads to a height sufficient to cause the parts to slide off the fork into the delivery chute. The analysis for the maximum fork inclination and the maximum rate of reciprocation would be similar to that presented in the previous subsection for the centerboard hopper. The number of parts selected by the fork per cycle would be obtained by experiment.

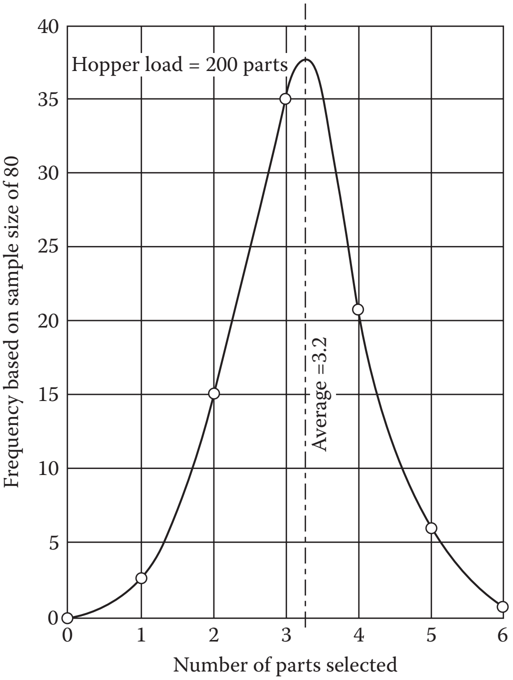


FIGURE 4.9 Frequency of part selection of a centerboard hopper.

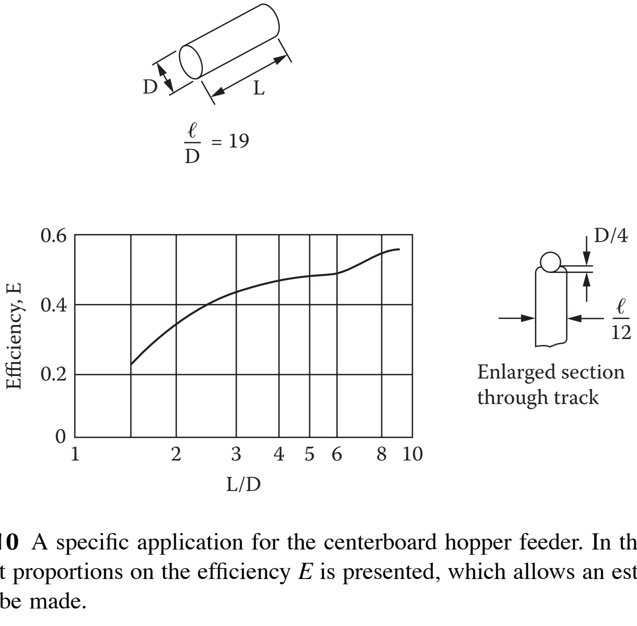


FIGURE 4.10 A specific application for the centerboard hopper feeder. In the figure, the effect of part proportions on the efficiency *E* is presented, which allows an estimate of the feed rate to be made.

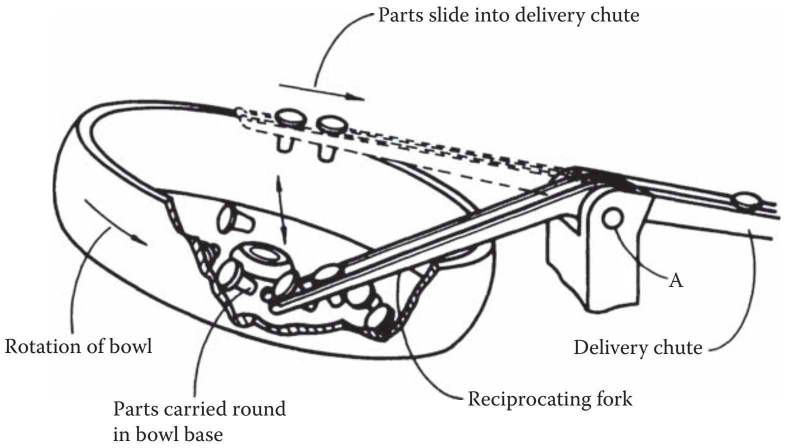

Parts slide into delivery chute
A
Rotation of bowl
Delivery chute
Reciprocating fork
Parts carried round in bowl base

FIGURE 4.11 Reciprocating-fork hopper.

4.4 EXTERNAL GATE HOPPER FEEDER

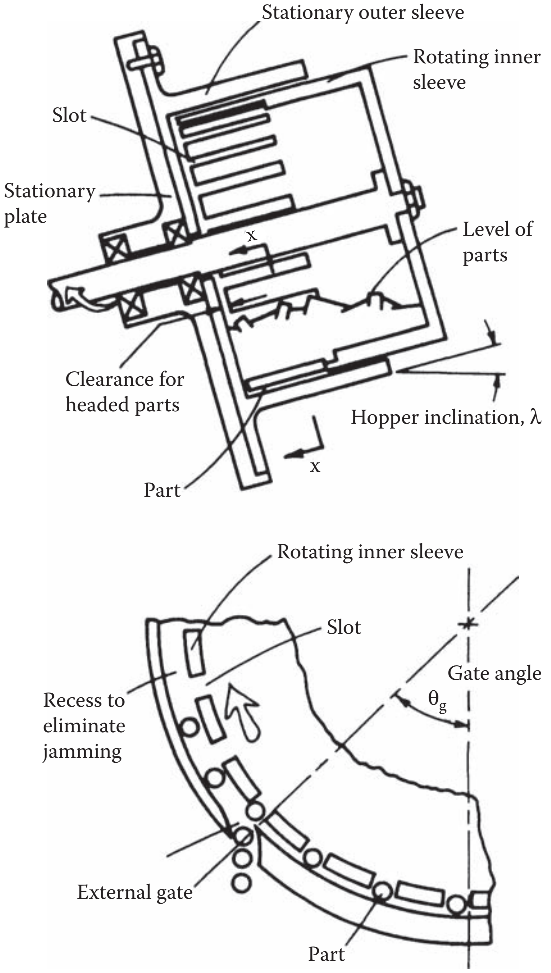
An external gate hopper (Figure 4.12) basically consists of a rotating cylinder having slots in its wall such that the cylindrical parts, if oriented correctly, can nest against the wall of the stationary outer sleeve. At some point, as the cylinder rotates, the slots pass over a gate in the outer sleeve, which allows the parts to drop one by one into the delivery chute. The tumbling action caused by rotation of the cylinder provides repeated opportunities for parts to fall into the slots and, subsequently, to pass through the external gate into the chute.

4.4.1 FEED RATE

Figure 4.13a shows an enlarged cross section of the slot and part just before the part falls through the gate. In the following analysis, an equation is developed for the maximum peripheral velocity of the inner cylinder that permits feeding to occur. Clearly, if the velocity is too high, the part will pass over the gate. At some limiting velocity v, the part will neither fall through the gate nor pass over it but will become jammed between corners B and C of the slot and gate as shown in Figure 4.13b. With any velocity below v, the part will drop through the gate as shown in Figure 4.13c. The position shown in Figure 4.13a represents the point at which the part starts to fall. In Figure 4.13b, the part has moved, from this position, a horizontal distance given by

$$D - 0.5(D^2 - h_g^2)^{1/2}$$

which, at a velocity v, represents a time interval of



Section on X-X

FIGURE 4.12 External gate hopper. General data: maximum peripheral velocity, 0.5 m/sec; gate angle θ_g, 0.79–1.13 rad (45–65°); hopper inclination λ, 0.17–0.26 rad (10–15°).

$$\frac{D - 0.5(D^2 - h_g^2)^{1/2}}{v}$$

During this time, the part has fallen a distance $(D/2 - h_g/2)$ and, if it is assumed that the part has fallen freely, the time taken is given by $[2(D/2 - h_g/2)/g]^{1/2}$. Thus, when these times are equated, the limiting velocity is given by

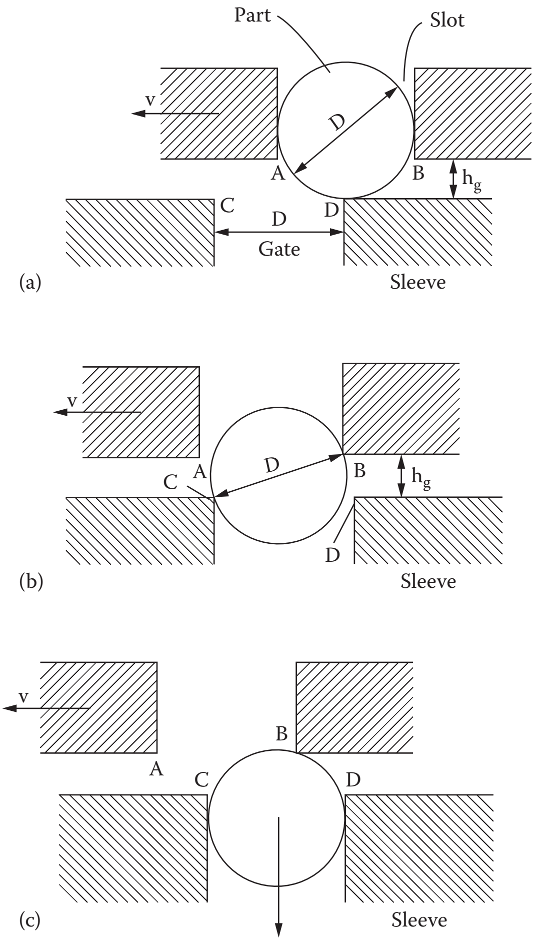


FIGURE 4.13 Various stages in the motion of a part passing through the gate of an external gate hopper.

$$\frac{D - 0.5(D^2 - h_g^2)^{1/2}}{v} = \left(\frac{D - h_g}{g}\right)^{1/2} \tag{4.17}$$

To give the largest values of v, the gap h_g between the cylinder and sleeve should be as large as possible. For values of h_g greater than $D/2$, there is a danger that the parts may become jammed between the corner B in the slot and the inner surface of the sleeve. Thus, taking $h_g = D/2$, Equation 4.17 becomes, after rearrangement,

$$v = 0.802\ (Dg)^{1/2} \tag{4.18}$$

If a_s is now taken to be the centerline distance between adjacent slots of the cylinder, the maximum feed rate $F_{\max}$ from the feeder is

$$F_{\max} = \frac{v}{a_s} = \frac{0.802}{a_s}(Dg)^{1/2} \tag{4.19}$$

In general, not all of the slots will contain parts and, if E is taken to be the efficiency of the feeder, the actual feed rate is given by

$$F = 0.802(Dg)^{1/2}\frac{E}{a_s} \tag{4.20}$$

The type of feeder analyzed in the preceding text is generally used for feeding rivets, in which the slots in the inner cylinder are open-ended to allow for the rivet heads. If the diameter of the rivet head is D_h, the minimum theoretical distance between the centers of the slots is D_h, and Equation 4.20 becomes

$$F = \frac{0.802(Dg)^{1/2}E}{D_h} = 0.802E\left(\frac{D}{D_h}\right)\left(\frac{g}{D}\right)^{1/2} \tag{4.21}$$

and, for plain cylindrical parts,

$$F = 0.802E\left(\frac{g}{D}\right)^{1/2} \tag{4.22}$$

where the partition between the parts is very small.

This analysis has considered the maximum feed rate from an external gate feeder. In practical designs, the actual feed rate will be less than this because of mechanical limitations, but the result indicates that certain trends might be expected from this type of feeder, and these are now summarized:

1. The maximum unrestricted feed rate is inversely proportional to the square root of the diameter of a cylindrical part.
2. When feeding rivets with the same head diameter, the maximum feed rate is proportional to the square root of the shank diameter; when feeding rivets in which the ratio of shank diameter to head diameter is fixed, the maximum feed rate is inversely proportional to the square root of the shank diameter.
3. If a high feed rate is required, the slots in the inner cylinder of the feeder should be as close as possible.

4.4.2 LOAD SENSITIVITY AND EFFICIENCY

The unrestricted feed rate for a given design of feeder depends on the efficiency *E*. This may be affected by the load in the hopper, the angle of inclination of the feeder axis, and the position of the external gate. Tests have shown that the most significant of these variables is the angle of inclination λ of the feeder axis. The results presented in Figure 4.14 indicate that λ should be as low as possible for maximum efficiency.

However, it should be realized that a practical limitation exists, because, as λ is reduced, the capacity of the hopper is also reduced, and a compromise must therefore be reached in any given design. A typical figure for λ is between 10° and 15°. The results in Figure 4.14 also show that the efficiency of the feeder increases rapidly as the hopper empties. Figure 4.15 shows the effect of the angular position ϕ_g of the external gate on the efficiency. It is clear that, for values of ϕ_g greater than 90°, the efficiency would become zero and, for very small values of ϕ_g, the chances of parts falling into the slots are reduced. The results show that an optimum exists when ϕ_g is approximately 45°, and Figure 4.14 shows that, with this optimum value and with the lowest practical value of 10° for λ, the minimum efficiency is 0.14. This represents (from Equation 4.20 when $\alpha_s = 2D$) a maximum possible feed rate of approximately 2 parts/sec with cylindrical parts of 7.94-mm (5/16-in.) diameter.

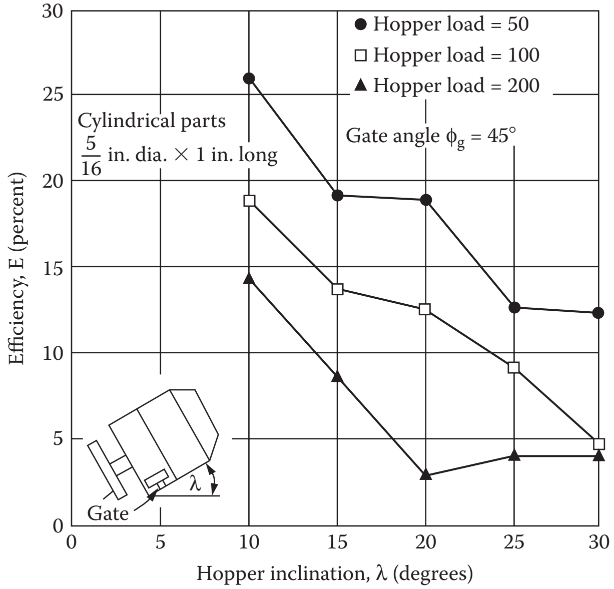


FIGURE 4.14 Effect of hopper inclination on the efficiency of an external gate hopper.

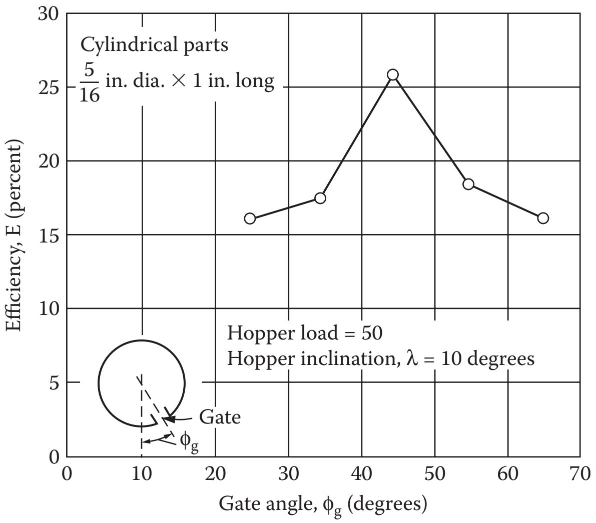


FIGURE 4.15 Effect of gate angle on the efficiency of an external gate hopper.

Figure 4.16 shows the application of the external gate hopper to the feeding of rivets. In the figure, the feed rate per slot FR_s is plotted against the peripheral velocity of the sleeve v.

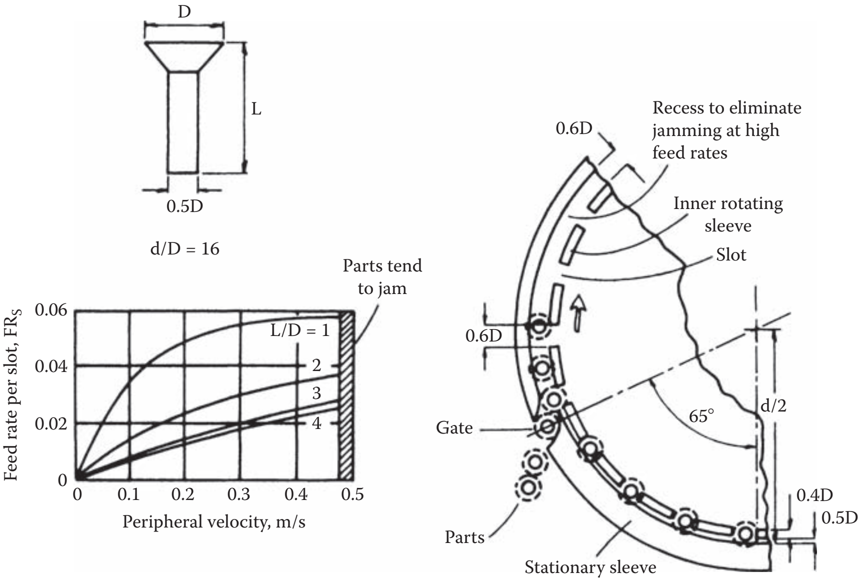


FIGURE 4.16 Performance of an external gate hopper when feeding headed parts.

4.5 ROTARY-DISK FEEDER

A typical rotary-disk feeder is illustrated in Figure 4.17. This feeder consists of a disk with a number of slots machined radially in its face and mounted at a steep angle to the horizontal, such that it forms the base of a stationary hopper. As the disk rotates, the parts in the hopper are disturbed by the ledges next to the slots. Some parts are caught in the slots and carried around until each slot, in turn, reaches the highest position, at which point it becomes aligned with a delivery chute down which the parts slide. A stationary circular plate at the center of the disk prevents the parts from sliding out of the slots until they are aligned with the chute.

In some designs of rotary-disk feeders, the length of the slots allows more than one part per slot to be selected during each revolution of the disk. This design will be analyzed first, and it will be assumed that, to give the greatest efficiency, the disk is indexed with sufficient dwell to allow all the parts selected in each slot to slide down the chute.

4.5.1 INDEXING ROTARY-DISK FEEDER

If a Geneva mechanism is employed to index a rotary-disk feeder, the time taken for indexing will be approximately equal to the dwell period. For the design

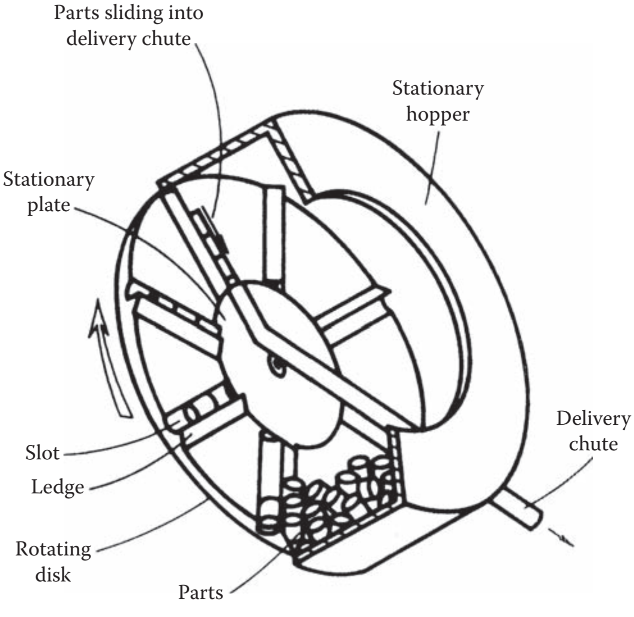


FIGURE 4.17 Rotary-disk feeder.

illustrated in Figure 4.17, the time t_s required for all parts in one slot to slide into the delivery chute is given by Equation 4.13:

$$t_s^2 = \frac{2\ell}{g(\sin\theta - \mu_d \cos\theta)} \tag{4.23}$$

where ℓ is the length of the slot, θ the inclination of the delivery chute, and μ_d the coefficient of dynamic friction between the part and the chute.

With a Geneva drive, the total period of an indexing cycle t_i is therefore given by

$$t_i = 2t_s = \left[\frac{8\ell}{g(\sin\theta - \mu_d \cos\theta)}\right]^{1/2} \tag{4.24}$$

If L is the length of a part, the maximum number that may be selected in a slot is ℓ/L. In practice, however, the average number selected will be less than this. If E is taken to be the efficiency of the feeder, the feed rate F will be given by

$$F = \frac{E\ell}{Lt_i} = E\left[\frac{\ell g(\sin\theta - \mu_d \cos\theta)}{8L^2}\right] \tag{4.25}$$

It can be seen from Equation 4.25 that if E is assumed to be constant:

1. The feed rate is independent of the number of slots in the disk.
2. For a given feeder, the feed rate is inversely proportional to the length of the part.
3. For maximum feed rate with a given part, μ_d should be as low as possible, and both the delivery chute angle θ and the slot length Rℓ should be as large as possible.

It is clear, however, that, with the design under consideration, the feed rate will be reduced as the hopper gradually empties almost completely, and no more than one part may be selected in each slot.

4.5.2 ROTARY-DISK FEEDER WITH CONTINUOUS DRIVE

A rotary-disk feeder with continuous drive would be most suitable for feeding disk-shaped parts. In this case, the analysis for the maximum feed rate would be similar to that for an external gate hopper because the situation in which the part slides from the slot into the delivery chute is similar to that shown in Figure 4.13. With this device, the slot length is equal to the diameter of the part D, and only one part can be selected in each slot. If the rotational speed of the disk is too high, the parts will pass over the mouth of the delivery chute, and feeding will not occur. If the effect of friction is considered negligible because of the large angle of inclination of the disk, the feed rate at maximum rotational speed will be given by Equation 4.22, which is

$$F = 0.802E\square\left(\frac{g}{D}\right)^{1/2}$$

where E is the efficiency of the feeder (that is, the average number of parts, selected per cycle, divided by the number of slots).

The foregoing analyses have considered the theoretical maximum feed rate from a rotary-disk feeder, both with indexing drive and with continuous drive. The results indicate that the following trends may be expected from this type of feeder:

1. For an indexing rotary-disk feeder with long slots, the maximum feed rate is inversely proportional to the length of the part and proportional to the square root of the slot length. For high feed rates, the slope of the delivery chute should be as large as possible, and the coefficient of friction between the part and the chute should be as low as possible.
2. For a feeder with continuous drive, the maximum feed rate for disk-shaped parts is inversely proportional to the square root of the diameter of the part.

4.5.3 LOAD SENSITIVITY AND EFFICIENCY

Tests were conducted on an indexing rotary-disk feeder with eight slots, each able to carry two cylindrical parts 25 mm (1 in.) in length and 8 mm (5/16 in.) in diameter. The results are presented in Figure 4.18, which shows that, as expected, the efficiency decreases as the hopper empties. This is because, for small loads, the mass of parts only partly covers the slots and, at best, only one part per slot can be selected during each cycle. The figure shows that both the efficiency and the load-sensitivity characteristics are improved as the angle of inclination θ' of the disk is reduced. Unfortunately, this also reduces the inclination angle θ of the delivery chute and increases the time taken for the parts to slide out of the slots. Clearly, in any given design, a compromise is necessary. In practice, typical values for the angles of inclination are 55–69° for the disk and 35° for the delivery chute. Figure 4.19 shows an application of the rotary-disk feeder in the feeding of disks.

4.6 CENTRIFUGAL HOPPER FEEDER

The centrifugal hopper feeder shown in Figure 4.20 is particularly suitable for feeding plain cylindrical parts. In this device, the parts are placed in a shallow

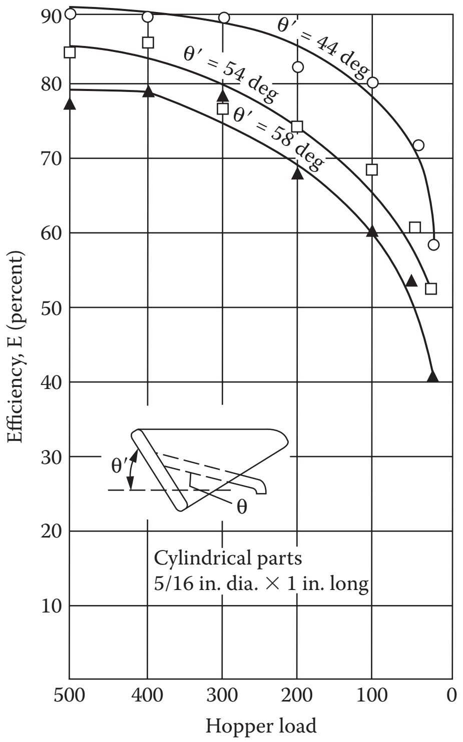


FIGURE 4.18 Load sensitivity of a rotary-disk feeder.

cylindrical hopper whose base rotates at constant speed. A delivery chute is arranged tangentially to the stationary wall of the hopper, and parts adjacent to this wall that have become correctly oriented because of the general circulation pass into the delivery chute. No orienting devices are provided in the hopper and, therefore, parts must be taken off in the attitude that they naturally adopt in the hopper, as indicated in the figure.

4.6.1 FEED RATE

If a part is moving with constant velocity v around the inside wall of a centrifugal hopper, the radial reaction at the hopper wall is equal to the centrifugal force $2m_pv^2/d$, where m_p is the mass of the part and d the diameter of the hopper. The frictional force F_w at the hopper wall tends to resist the motion of the part and is given by

$$F_w = \frac{2\mu_w m_p v^2}{d} \qquad (4.26)$$

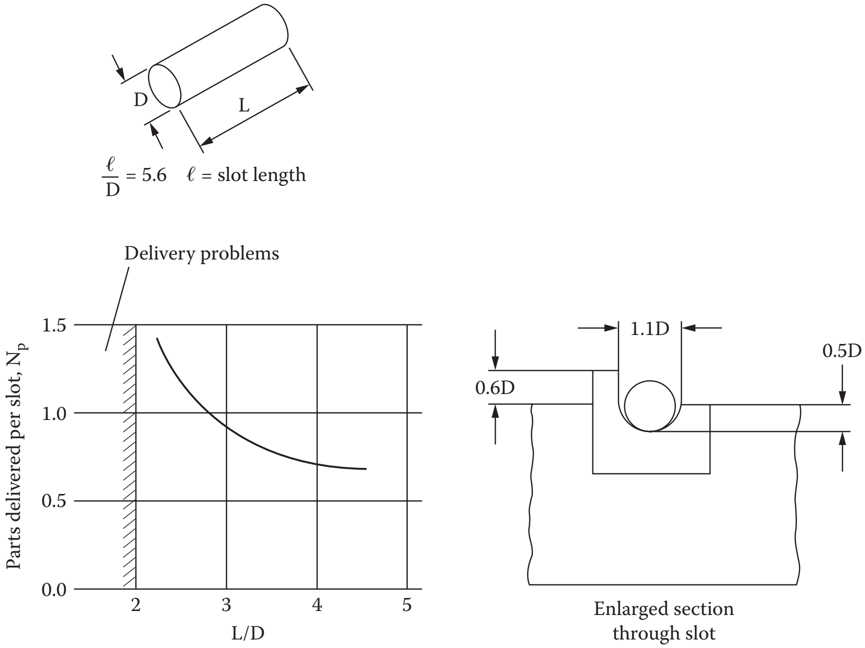


FIGURE 4.19 Performance of a rotary-disk feeder when feeding disks.

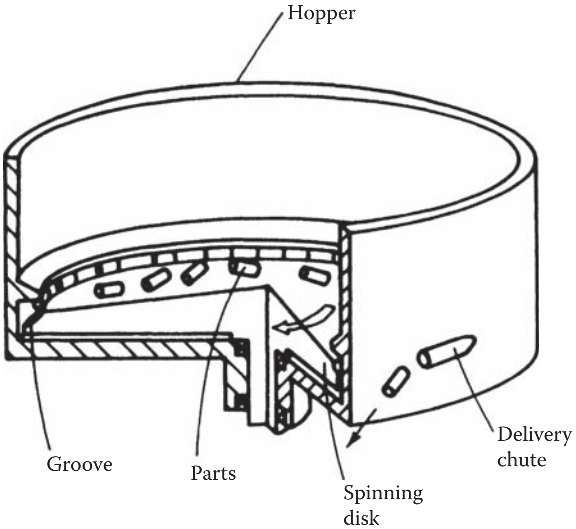


FIGURE 4.20 Centrifugal hopper.

where μ_w is the coefficient of friction between the part and the hopper wall. When the peripheral velocity of the spinning disk is greater than v, the disk slips under the part, and the frictional force F_b between the part and the spinning disk is given by

$$F_b = \mu_b m_p g \tag{4.27}$$

where μ_b is the coefficient of friction between the part and the spinning disk. Because, under this condition, $F_b = F_w$, setting Equation 4.26 equal to Equation 4.27 gives

$$v = \left[\frac{g\mu_b d}{2\mu_w}\right]^{1/2} \tag{4.28}$$

and the maximum feed rate $F_{\max}$ of parts of length L is given by

$$F_{\max} = \frac{v}{L} = \frac{(g\mu_b d/2\mu_w)^{1/2}}{L} \tag{4.29}$$

and the actual feed rate F may be expressed as

$$F = E\square\left[\frac{(g\mu_b d/2\mu_w)^{1/2}}{L}\right] \tag{4.30}$$

where E is the feeder efficiency.

Equation 4.30 shows that the unrestricted feed rate from a centrifugal hopper is proportional to the square root of the hopper diameter and inversely proportional to the length of the parts.

Using Equation 4.28, the maximum rotational frequency $n_{\max}$ of the spinning disk, above which no increase in feed rate occurs, is

$$n_{\max} = \frac{v}{\pi d} = \frac{[(g/2d)(\mu_b/\mu_w)]^{1/2}}{\pi} \tag{4.31}$$

This equation is plotted in Figure 4.21 and can be used to choose the maximum rotational frequency of the hopper.

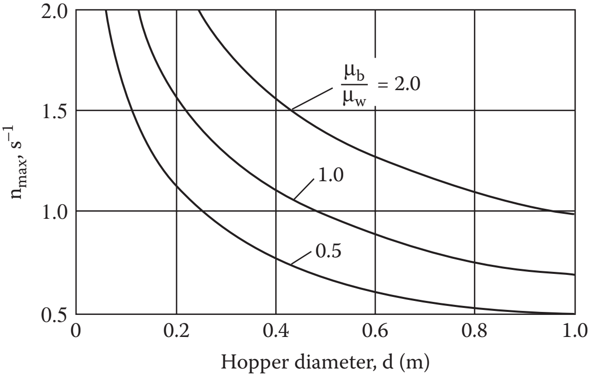


FIGURE 4.21 Maximum rotational frequency for a centrifugal hopper, in which n_{max} is the maximum rotational frequency of the disk, μ_b the coefficient of friction between the part and the spinning disk, and μ_w the coefficient of friction between the part and the stationary hopper wall.

4.6.2 EFFICIENCY

The overall efficiency E of the hopper can be determined only by experiment. Figure 4.22 plots results of experiments showing the effect of rotational frequency on efficiency when plain cylinders are fed.

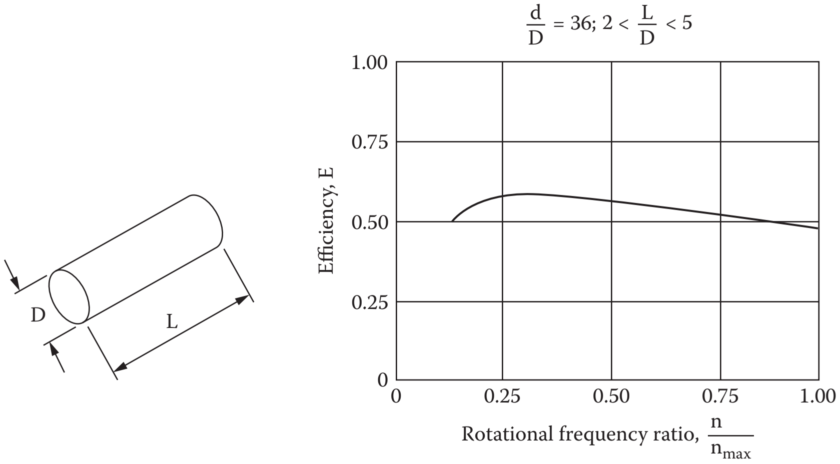


FIGURE 4.22 Performances of a centrifugal hopper when feeding cylinders (d = hopper diameter).

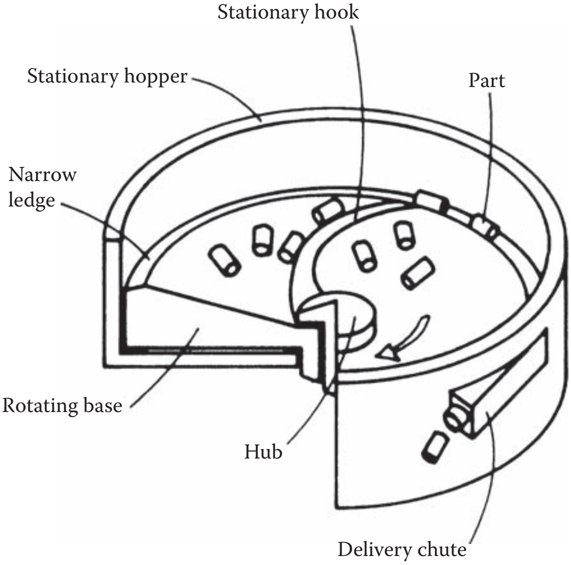


FIGURE 4.23 Stationary-hook hopper.

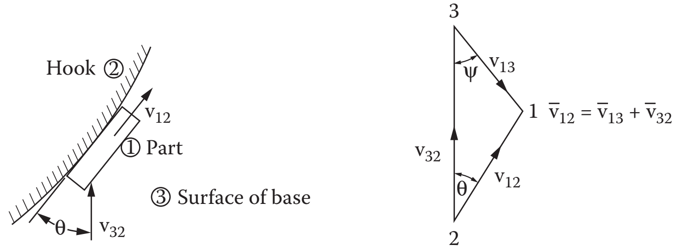
4.7 STATIONARY-HOOK HOPPER FEEDER

In the stationary-hook hopper parts feeder (Figure 4.23), the curved hook is stationary, and the concave base of the hopper rotates slowly beneath it. The parts are guided along the edge of the hook toward a ledge at the periphery of the hopper, where they are eventually deflected into the delivery chute by a deflector mounted on the hopper wall. One advantage of this type of feeder is its gentle feeding action, which makes it suitable for feeding delicate parts at low speed.

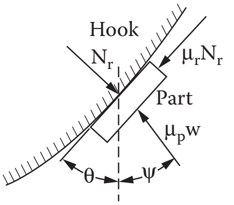
4.7.1 DESIGN OF THE HOOK

Ideally, the stationary hook should be designed such that a part travels along its leading edge with constant velocity. With reference to Figure 4.24a, the velocity of the part relative to the hook is designated v_{12}, and the velocity of a point on the moving surface of the base relative to the hook is designated v_{32}. The direction of the velocity v_{13} of the part relative to the base is then obtained from the velocity diagram, Figure 4.24b.

The frictional force between the part and the moving surface is in the direction opposite to the relative velocity v_{13} and is the force that causes the part to move along the hook. The direction of this force is specified by ψ in Figure 4.24b. By the law of sines,



(a) Nomenclature (b) Velocity diagram



(c) Horizontal forces acting on part

FIGURE 4.24 Analysis of stationary-hook hopper.

$$\frac{v_{12}}{v_{32}} = \frac{\sin \psi}{\sin (\theta + \psi)} \tag{4.32}$$

where θ is the angle between the velocity vector v_{32} and the tangent to the hook at the point under consideration.

Neglecting the inertia force, the external forces acting on the part in the horizontal plane are shown in Figure 4.24c. When these forces are resolved parallel and normal to the hook tangent, the conditions for equilibrium are

$$\mu_r N_r = \mu_p W \cos (\theta + \psi) \tag{4.33}$$

$$N_r = \mu_p W \sin (\theta + \psi) \tag{4.34}$$

where μ_r is the coefficient of dynamic friction between the part and the hook, μ_p the coefficient of sliding friction between the part and the moving surface, N_r the normal reaction between the part and the hook, and W the weight of the part. Combining Equation 4.33 and Equation 4.34 give

$$\mu_r = \cot (\theta + \psi) \tag{4.35}$$

Equation 4.32 and Equation 4.35 can be combined to eliminate ψ

$$\frac{v_{12}}{v_{32}} = \cos \boxplus - \mu_r \sin \boxplus \qquad (4.36)$$

The velocity of a point on the base relative to the hook is given by

$$v_{32} = 2\pi r n \qquad (4.37)$$

where r is the distance from the point under consideration to the center of the hopper and n the rotational frequency of the hopper base. For constant speed of the part along the hook, Equation 4.36 and Equation 4.37 can be combined to give

$$r(\cos \theta - \mu_r \sin \theta) = K \qquad (4.38)$$

where K is a constant given by $v_{12}/2\pi n$.

An explicit equation defining the shape of the hook is not readily obtained from Equation 4.38. However, a numerical method was used [2] to develop the hook shapes, giving constant-speed feeding for various values of the coefficient of sliding friction between the part and the hook; these hook shapes are presented in Figure 4.25. A computer program constructed the hook shapes, using straight-

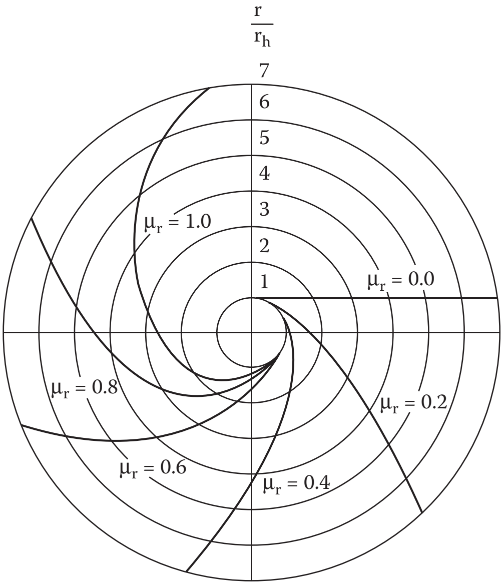


FIGURE 4.25 Hook shapes for a stationary-hook hopper, in which r_h is the radius of the hub and r is the radial location of a particular point on the hook. Maximum peripheral velocity is 0.4 m/sec. (From Boothroyd, G. and Zinsmeister, G. E., Design of Stationary Hook Hoppers for Feeding Delicate Parts, *Automation*, May 1969, pp. 64–66. With permission.)

line segments starting at the hub and working outward. The results in Figure 4.25 are plotted in a dimensionless form in which the radius to a point on the hook is divided by the hub radius.

In using these results to design the shape of a hook for a particular application, it is always preferable to use a larger-than-expected value of the coefficient of sliding friction between the part and the hook. This ensures that parts will not decelerate as they move along the hook and thus tends to avoid jamming in the feeding process.

4.7.2 FEED RATE

It is apparent that the velocity of the parts along the hook will determine the maximum feeder output. For parts of a given length being fed end to end, the maximum output per unit of time is determined by dividing the velocity at the hub by the individual part length. Figure 4.26 shows how the maximum feed rate from the feeder varies with the length of parts for various rotational frequencies.

For particular applications, the actual feed rate will be lower than that given in Figure 4.26. For a particular design of feeder, the feed rate can be expressed by

$$F = \frac{E\pi dn}{L} \tag{4.39}$$

where d is the hopper diameter, n the rotational frequency of the disk, L the part length, and E the efficiency of the feeder. Figure 4.27 illustrates an application

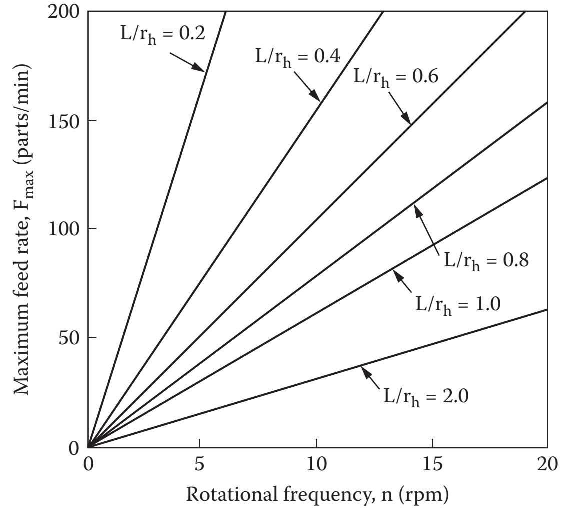


FIGURE 4.26 Maximum feed rate for a stationary-hook hopper, in which $F = (r_h L)(2\pi n)$, with L the length of the part and r_h the feeder hub radius.

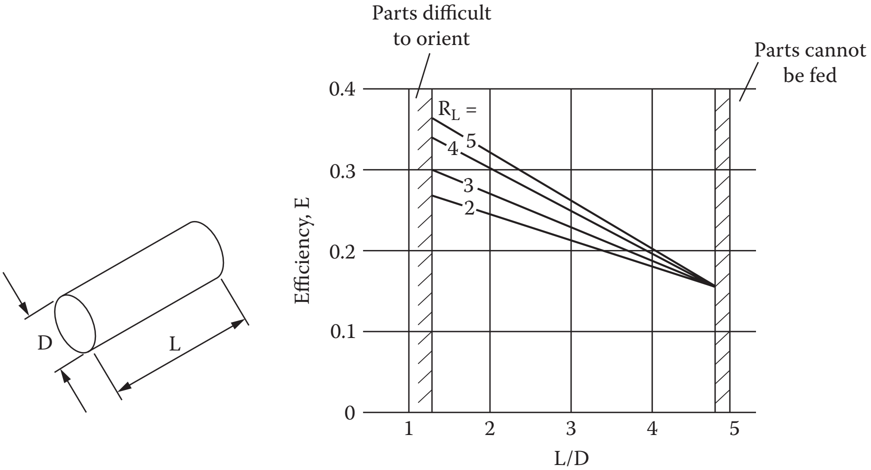


FIGURE 4.27 Performance of a stationary-hook hopper when feeding cylinders, in which load ratio $R_L = LN/\pi D$, $d/D = 36$, and N is the number of parts in the hopper.

of the stationary-hook hopper to the feeding of cylinders, in which the effect of part proportions on the feeder efficiency is presented.

4.8 BLADED-WHEEL HOPPER FEEDER

In the bladed-wheel hopper feeder (Figure 4.28), the tips of the blades of a vertical multibladed wheel run slightly above a groove in the bottom of the hopper. The groove has dimensions such that the parts in the hopper may be accepted by the groove in one particular orientation only. Rotation of the wheel agitates the parts in the hopper and causes parts arriving at the delivery point in the wrong attitude to be pushed back into the mass of parts.

The angle of inclination of the track is generally about 45°, and the maximum linear velocity of the blade tip is around 0.4 m/sec. Figure 4.29 shows an application of the bladed-wheel hopper to the feeding of cylinders.

4.9 TUMBLING-BARREL HOPPER FEEDER

In the tumbling-barrel hopper feeder (Figure 4.30), the cylindrical container, which has internal radial fins, rotates about a horizontal vibratory feed track. Parts placed in bulk in the hopper are carried upward by the fins until, at some point, they slide off the fin and cascade onto the vibratory feed track. The feed track is shaped to suit the required orientation of the part being fed and retains and feeds those parts only in this orientation. This feeder is suitable for feeding a wide variety of parts, such as cylinders, U-shaped parts, angled parts, and prisms.

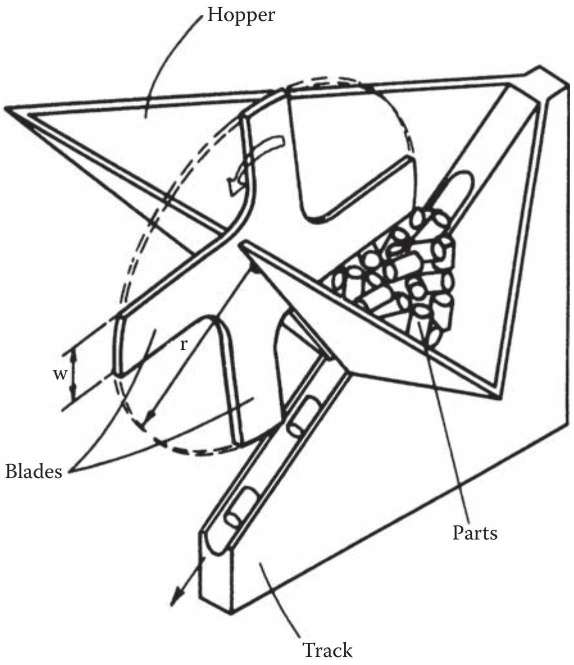


FIGURE 4.28 Bladed-wheel hopper.

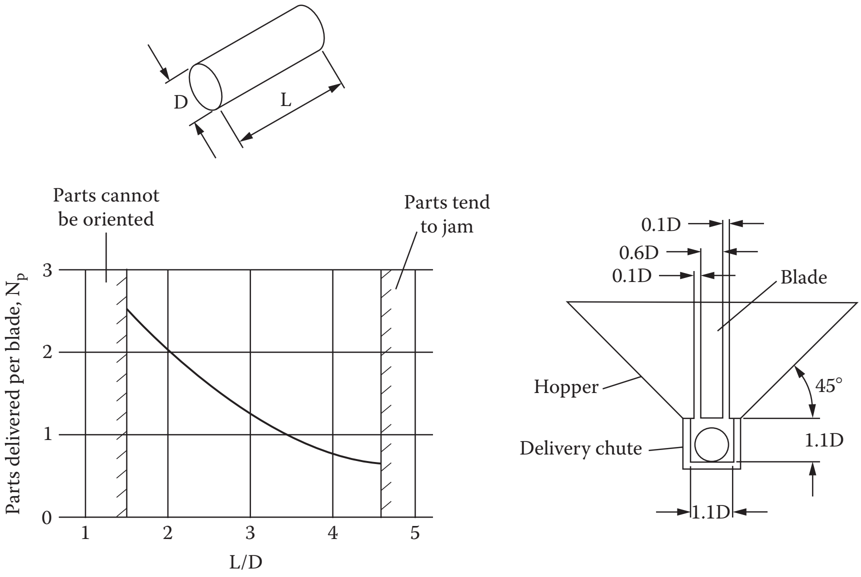


FIGURE 4.29 Performance of bladed-wheel hopper when feeding cylinders.

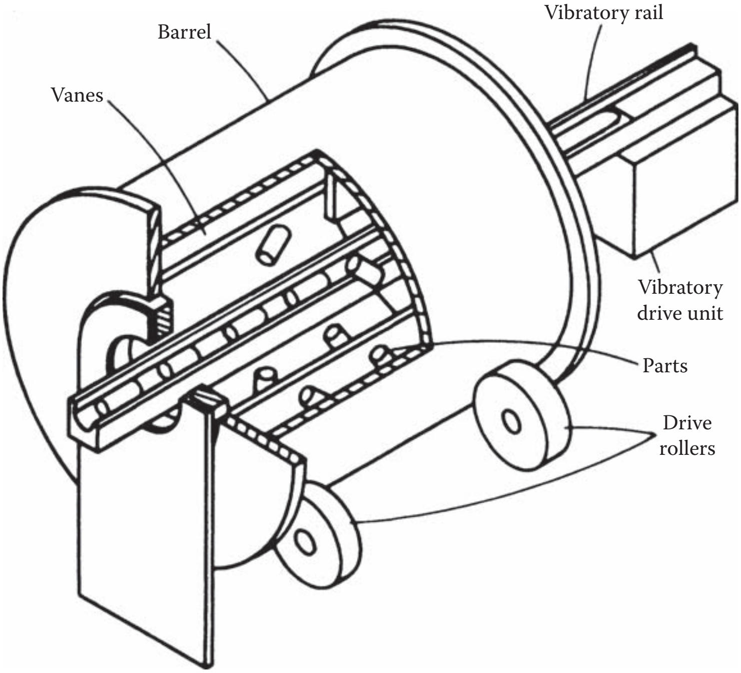


FIGURE 4.30 Tumbling-barrel hopper.

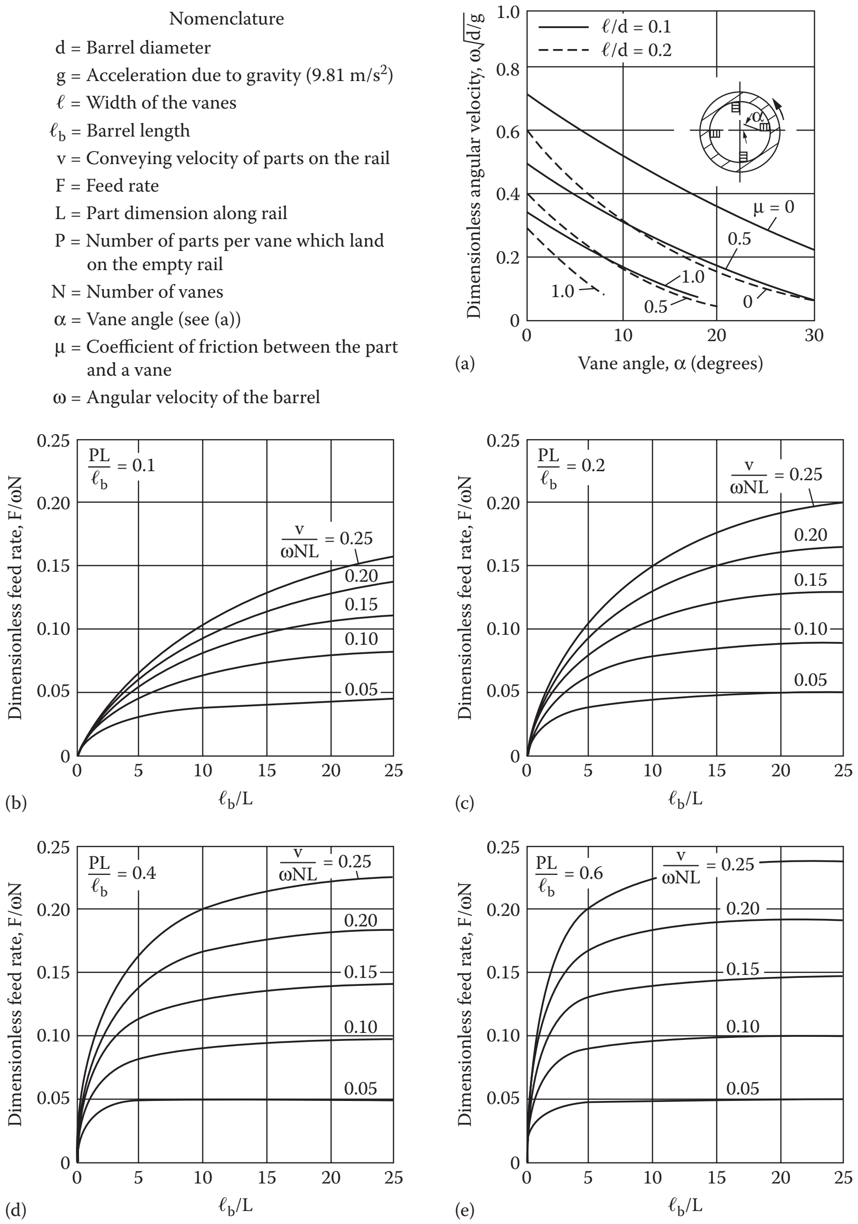
The optimum hopper load is that which fills the barrel to a height of one-fourth the inside diameter. For parts that can stack on one another, it is necessary to provide the outlet with a stationary gate, which outlines the shape of a part on the rail so that parts come out in a single layer only. Rubber or cork may be placed along the inside wall of the barrel to reduce noise and damage to parts.

4.9.1 FEED RATE

For a part whose motion relative to the vanes is one of pure translation (that is, the part does not roll), the rotational frequency that maximizes the number of parts that land on a rail passing through the barrel center can be determined from Figure 4.31a. The result may not be valid for parts whose motion relative to the vanes contains rotational components.

Figure 4.31b to Figure 4.31e can be used to estimate the values of the barrel design parameters that achieve a given feed rate. To use the graphs, it is first necessary to determine, by observation, the average number of parts that land on an empty rail per vane *P*.

Figures 4.32 and Figure 4.33 show applications of the tumbling-barrel hopper to the feeding of cylinders and U-shaped parts, respectively.



Nomenclature

d = Barrel diameter

g = Acceleration due to gravity (9.81 m/s^2)

ℓ = Width of the vanes

ℓ_b = Barrel length

v = Conveying velocity of parts on the rail

F = Feed rate

L = Part dimension along rail

P = Number of parts per vane which land on the empty rail

N = Number of vanes

α = Vane angle (see (a))

μ = Coefficient of friction between the part and a vane

ω = Angular velocity of the barrel

(a)
Dimensionless angular velocity, $\omega\sqrt{d/g}$
Vane angle, α (degrees)
0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
$\ell/d = 0.1$
$\ell/d = 0.2$
α
μ = 0
0.5
1.0
0
0.5
1.0
(b)
(c)
(d)
(e)
Dimensionless feed rate, F/ωN
ℓ_b/L
0
0.05
0.10
0.15
0.20
0.25
0
5
10
15
20
25
$\frac{PL}{\ell_b} = 0.1$
$\frac{PL}{\ell_b} = 0.2$
$\frac{PL}{\ell_b} = 0.4$
$\frac{PL}{\ell_b} = 0.6$
$\frac{v}{\omega NL} = 0.25$
0.20
0.15
0.10
0.05

FIGURE 4.31 Feed rate for a tumbling-barrel hopper.

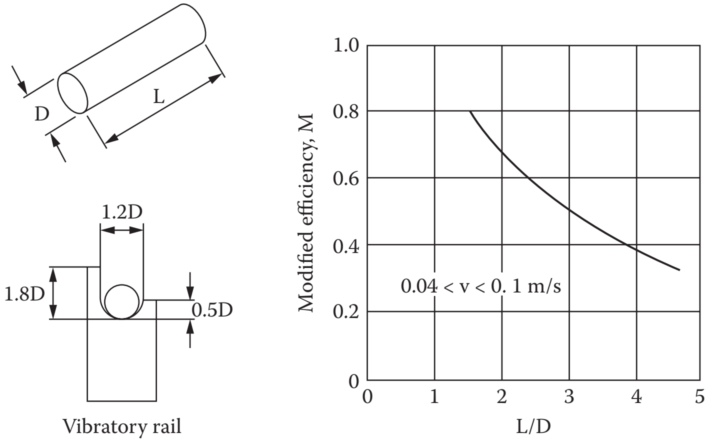


FIGURE 4.32 Performance of a tumbling-barrel hopper when feeding cylinders. The feed rate is $Mv/L + 0.7$ parts/sec, where M is the modified efficiency, v the conveying velocity on the vibratory rail (m/sec), and L the part length (m). The ratio of barrel length to diameter d is 1.2; $d/D = 21$.

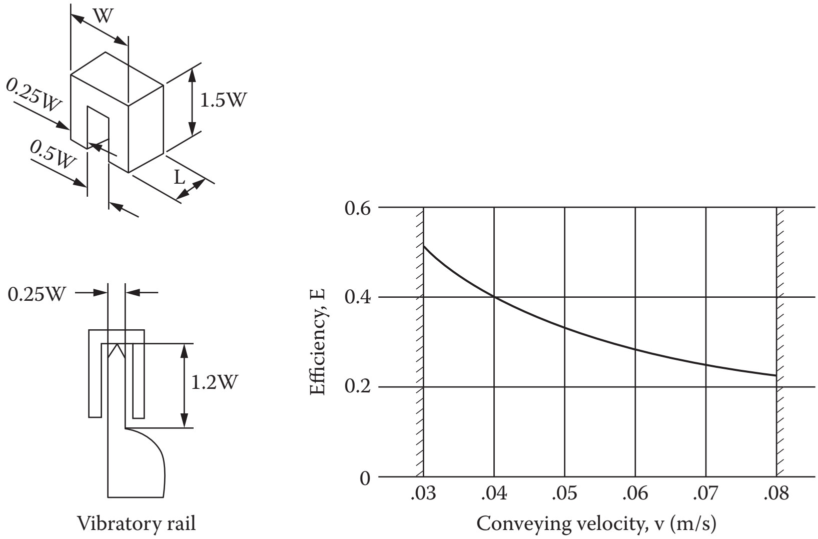


FIGURE 4.33 Performance of a tumbling-barrel hopper when feeding U-shaped parts. The feed rate is Ev/L, where E is the efficiency, v the conveying velocity on the vibratory rail, and L the part length. The ratio of barrel length to diameter d is 1.2; $d/W = 13$; and $0.4 < L/W < 1.2$.

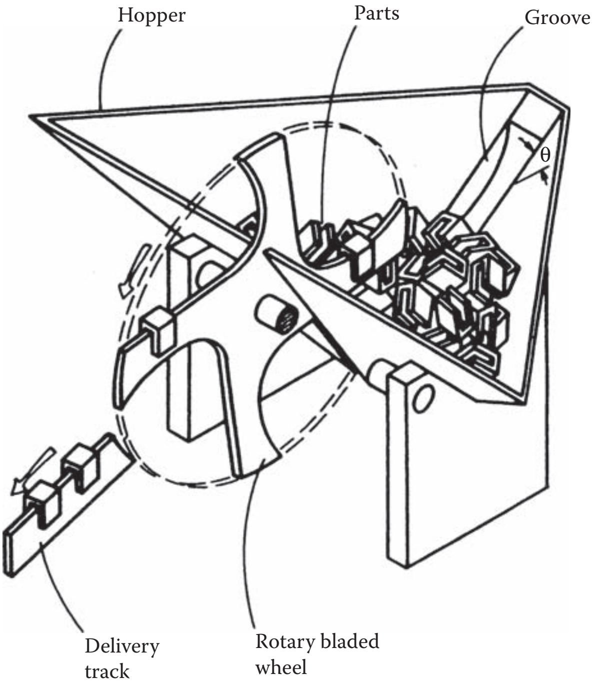


FIGURE 4.34 Rotary-centerboard hopper.

4.10 ROTARY-CENTERBOARD HOPPER FEEDER

This feeder (Figure 4.34) consists of a bladed wheel that rotates inside a suitably shaped hopper. The edges of the blades are profiled to collect parts in the desired attitude and lift them clear of the bulk of the parts. Further rotation of the wheel causes the oriented parts to slide off the blade, which is then aligned with the delivery chute. It is usual to drive the wheel intermittently by either a Geneva mechanism or a ratchet-and-pawl mechanism. The design of the indexing mechanism should take into account the dwell time required for a full blade to discharge all its parts when aligned with the delivery chute. An analysis similar to that used for the reciprocating-centerboard hopper feeder gives the minimum values for dwell and indexing times and, hence, the maximum feed rate.

The peripheral velocity of the rotary bladed wheel should be no greater than 0.6 m/sec. Figure 4.35 shows the application of the feeder to the feeding of U-shaped parts.

4.11 MAGNETIC-DISK FEEDER

This feeder (Figure 4.36) consists of a container that is closed at one side by a vertical disk. The disk rotates about a horizontal axis, and permanent magnets

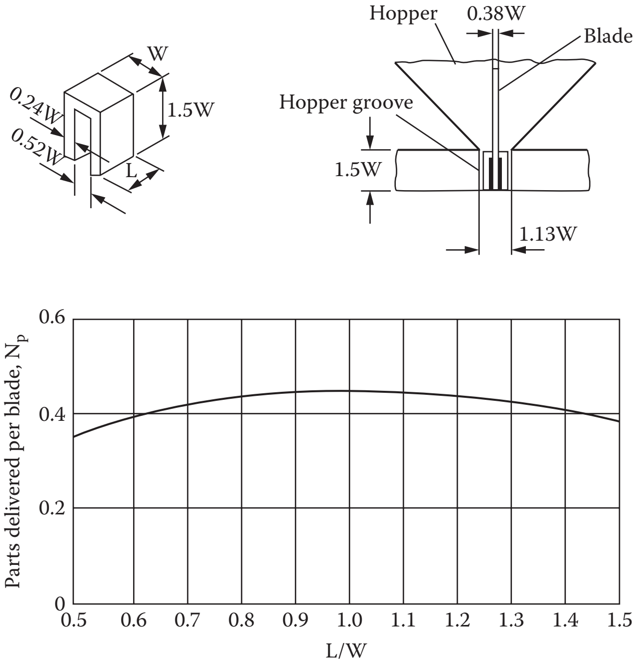


FIGURE 4.35 Performance of a rotary-centerboard hopper when feeding U-shaped parts.

are inserted in pockets around its periphery. As the disk rotates, parts are lifted by the magnets and stripped off at a convenient point. This feeder can clearly be used only for parts of a ferromagnetic material.

The magnets should have a holding capacity of 10–20 times the weight of one part and a diameter approximately equal to the major dimension of the part. The linear velocity of the magnets should be 0.08–0.24 m/sec. Figure 4.37 shows an application of the feeder to the feeding of disks of various proportions.

4.12 ELEVATING HOPPER FEEDER

This feeder (Figure 4.38) has a large hopper with inclined sides. Often, an agitating device is fitted to the base to cause the parts to slide to the lowest point in the hopper. An endless conveyor belt, fitted with a series of selector ledges, is arranged to elevate parts from the lowest point in the hopper. The ledges are shaped such that they will accept parts only in the desired attitude. The parts slide off the ledges into the delivery chute, which is situated at a convenient point above the hopper. Figure 4.39 shows the application of this feeder in the feeding of cylinders.

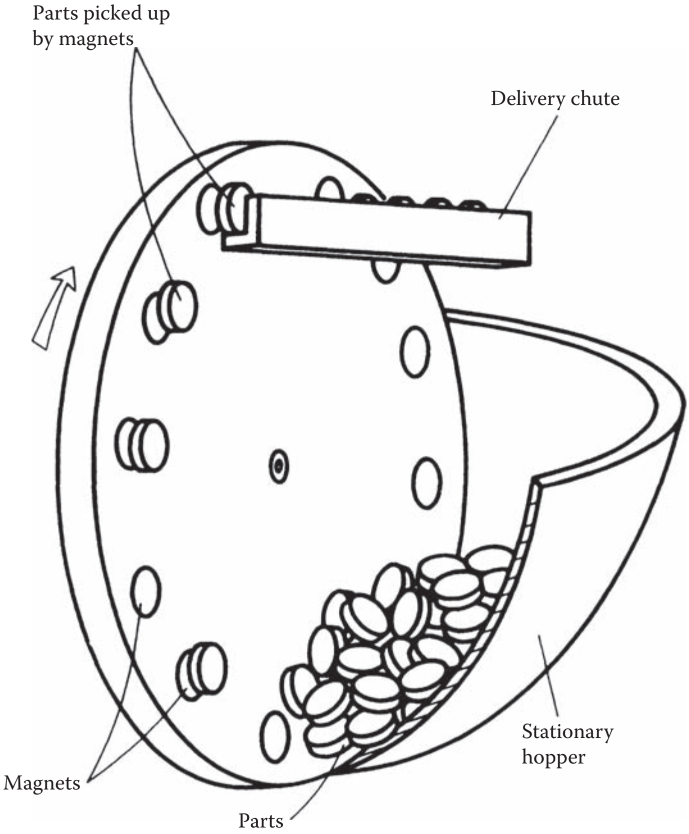


FIGURE 4.36 Magnetic-disk feeder.

4.13 MAGNETIC ELEVATING HOPPER FEEDER

The magnetic elevating hopper feeder (Figure 4.40) is basically the same as the elevating hopper feeder except that, instead of ledges, permanent magnets are fitted to the endless belt. Thus, the feeder is suitable only for handling ferromagnetic materials and cannot easily be used for orientation purposes. This feeder is usually used to strip the parts from the magnets at the top of the belt conveyor.

4.14 MAGAZINES

An alternative means of delivering parts to an automatic assembly machine is to use a magazine. With this method, parts are stacked into a container or magazine that constrains the parts in the desired orientation. The magazine is then attached to the workhead of the assembly machine. The magazines may be spring-loaded

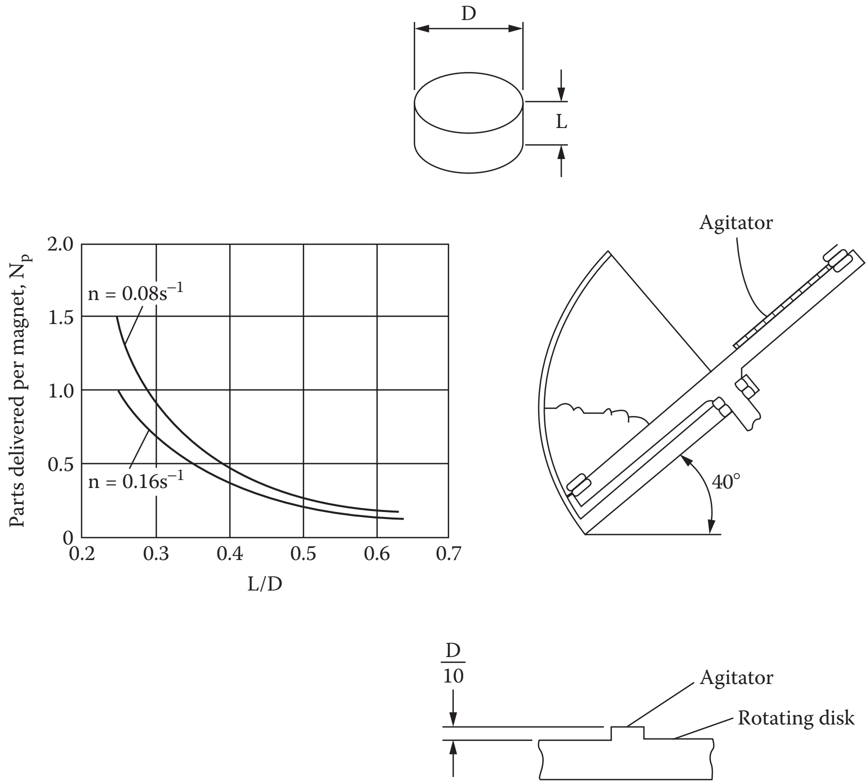


FIGURE 4.37 Performance of magnetic-disk feeder when feeding disks (*n* = rotational frequency).

to facilitate delivery of the parts or, alternatively, the parts may be fed from the magazine under gravity or assisted by compressed air.

Magazines have several advantages over conventional parts feeders, and some of these are described in the following list:

1. In some cases, magazines may be designed to accept only those parts that would be accepted by the assembly machine workhead and thus can act as inspection devices. This can lead to considerable reduction in the downtime on the assembly machine.
2. Magazines can often replace not only the parts feeder but also the feed track.
3. Magazines are usually very efficient feeding devices, and assembly machine downtime due to feeder or feed track blockages can often be eliminated by their use.

Some benefits may be obtained if the magazines are loaded at the assembly factory. If a number of similar parts are to be used in an assembly, it may be

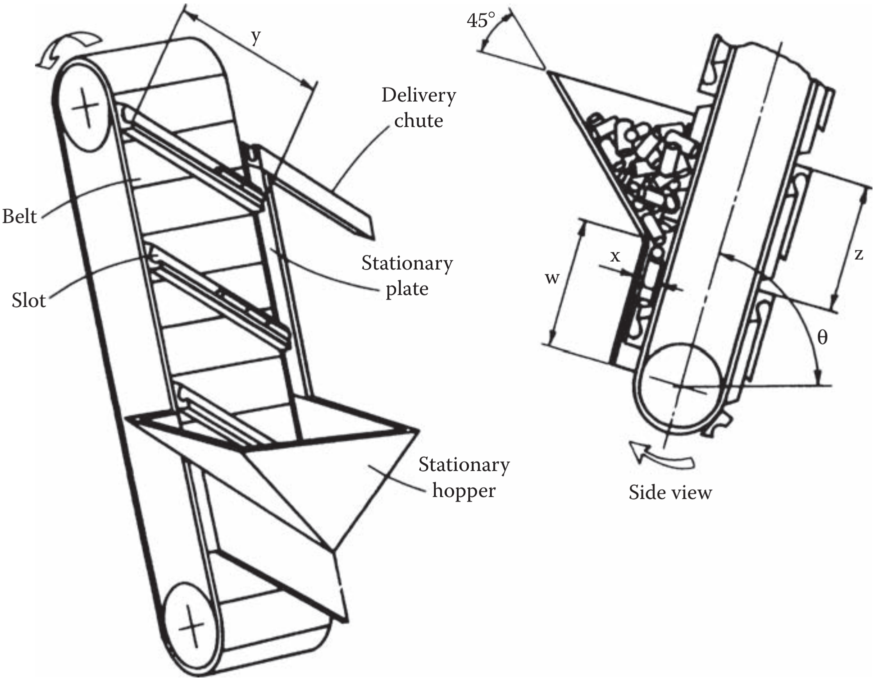


FIGURE 4.38 Elevating hopper feeder.

possible to use one hopper feeder to load all the required magazines. Further, if the magazine is designed to accept only good parts, or if some method of inspecting the parts is incorporated into the parts feeder, downtime will occur on the magazine loader and not on the assembly machine.

Some of the disadvantages associated with the use of magazines are as follows:

1. Magazines will generally hold considerably fewer parts than the alternative parts feeder, and magazine changes must therefore be made more frequently than the refilling of the parts feeder.
2. The most suitable place to load the magazines is the point at which the part is manufactured because it is at this point that the part is oriented. When manufacture and assembly take place in the same factory, this may not present a serious problem but, if the parts are purchased from another firm, it will be much more difficult to arrange for magazine loading.
3. The cost of magazines can be considerable and prohibitive. The cost and life expectancy should be included in any economic analysis.

In some cases, it is possible to use disposable magazines such as those employed in the packaging of certain drugs. Such a magazine can be fed to the

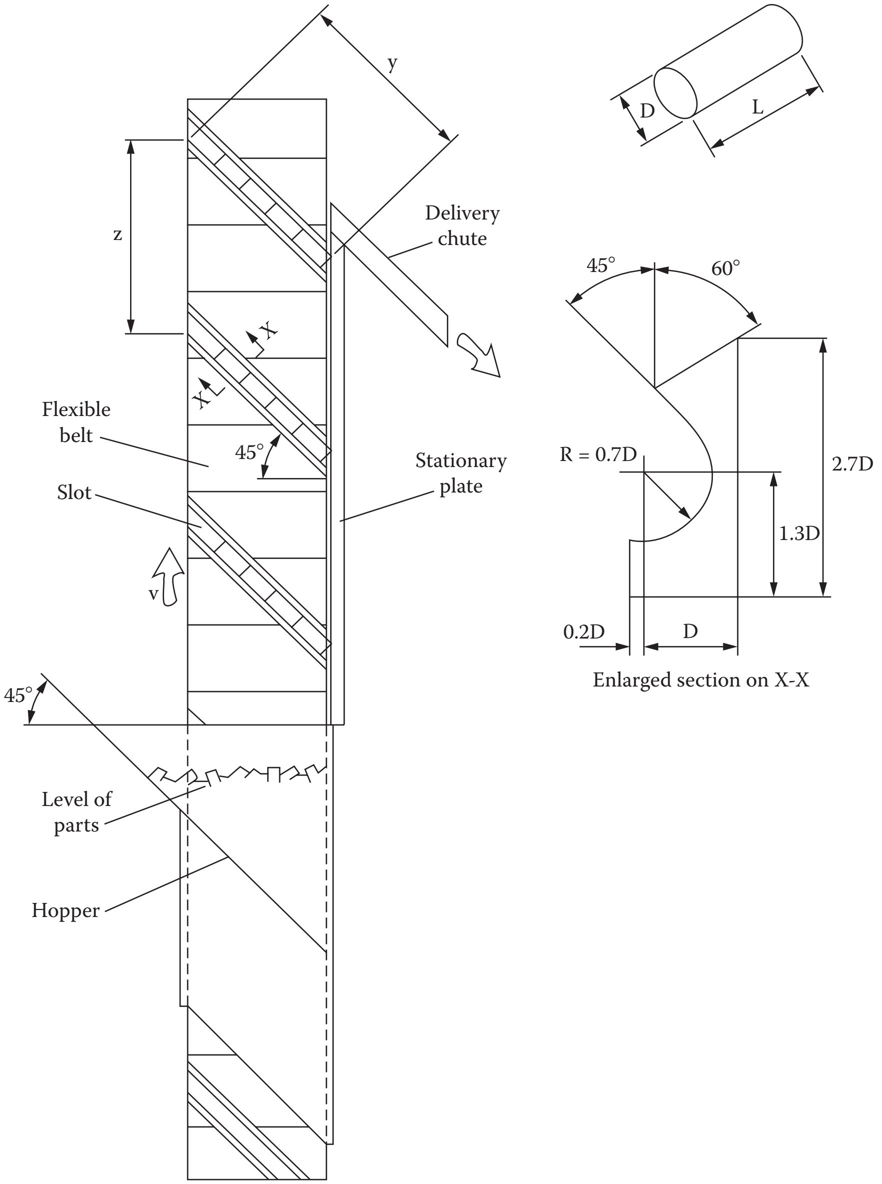


FIGURE 4.39 Performance of an elevating hopper feeder when feeding cylinders. The feed rate is 0.6 yv/zL, where v is the velocity of the belt, y the length of one slot, z the distance between two slots, and L the part length; $L/D > 2$; $y/l > 4$.

workhead, which would have a suitable mechanism for extracting the parts. Another alternative is to blank parts from a strip. In this case, the final operation of separating the parts from the strip can be left to the assembly machine workhead.

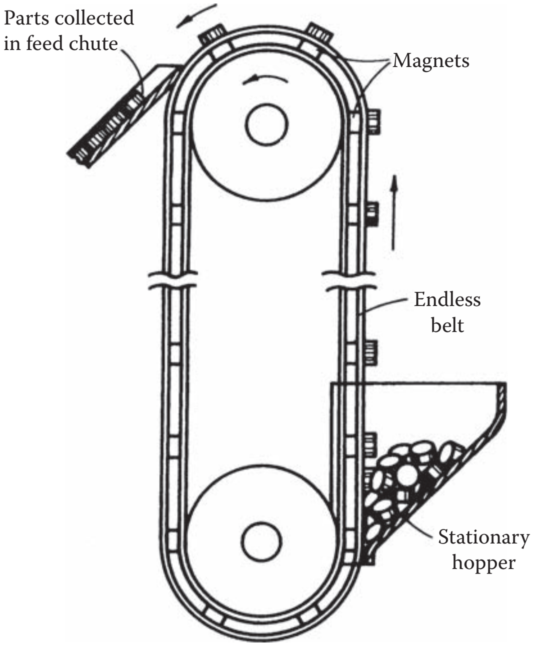


FIGURE 4.40 Magnetic elevating hopper feeder.

A further alternative often used for small blanked parts is for the blanking operation to take place on the machine just prior to the point at which the part is required in the assembly.

REFERENCES

1. Boothroyd, G., Poli, C., and Murch, L.E., *Handbook of Feeding and Orienting Techniques for Small Parts*, University of Massachusetts, Amherst, MA, 1977.
2. Boothroyd, G. and Zinsmeister, G.E., Design of Stationary Hook Hoppers for Feeding Delicate Parts, *Automation*, May 1969, pp. 64–66.

5 Feed Tracks, Escapements, Parts-Placement Mechanisms, and Robots

To provide easy access to automatic workheads and the assembly machine, the parts feeders are usually placed some distance away from the workheads. The parts, therefore, have to be maintained in their orientation and transferred between the feeder and the workhead by using a feed track. Most parts feeders do not supply parts at the discrete intervals usually required by an automatic workhead. As a result, the parts feeder must be adjusted to overfeed slightly, and a metering device, usually referred to as an *escapement*, is necessary to ensure that the parts arrive at the automatic workheads at correct intervals. After leaving the escapement, the parts are placed in the assembly, a process usually carried out by a parts-placing mechanism or a robot.

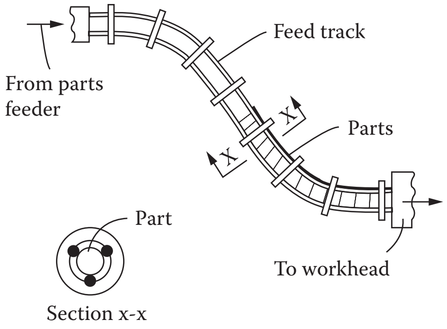
5.1 GRAVITY FEED TRACKS

Feed tracks may be classified as either gravity tracks or powered tracks. The majority of tracks are of the gravity type, and these may take many forms. Two typical track arrangements are illustrated in Figure 5.1; the choice of the design generally depends on the required direction of entry of the parts into the workhead. In design, it should be remembered that the track may not always be full, and it is desirable that feeding should still take place under this condition.

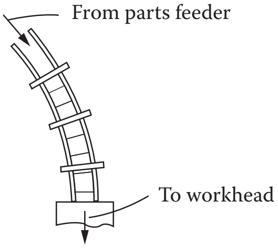
When the track is partly full and no pushing action is obtained by air jets or vibration, it is clear that the vertical-delivery track design shown in Figure 5.1b will deliver parts from rest at a greater rate than the horizontal-delivery design shown in Figure 5.1a. The performance of the vertical-delivery track will also be independent of the loading in the track and, if no further parts are fed into it, the track will deliver the last part as quickly as the first. The time of delivery t_p will be given by the time taken for a part to fall a distance equal to its own length.

Thus,

$$t_p = \left(\frac{2L}{g}\right)^{1/2} \tag{5.1}$$



(a) Horizontal delivery of parts



(b) Vertical delivery of parts

FIGURE 5.1 Gravity feed track arrangements.

where L is the length of the part and g is the acceleration resulting from gravity equal to 9.81 m/sec^2.

5.1.1 ANALYSIS OF HORIZONTAL-DELIVERY FEED TRACK

In the track design for horizontal delivery (Figure 5.1a), the last few parts cannot be fed and, even if the height of parts in the track is maintained at a satisfactory level, the delivery time will be greater than that given by Equation 5.1.

Figure 5.2 shows the basic parameters defining the last portion of a horizontal-delivery gravity feed track. This portion consists of a horizontal section AB of length L_1, preceded by a curved portion BC of constant radius R, which, in turn, is preceded by a straight portion inclined at an angle α to the horizontal. It is assumed in the following analysis that a certain fixed number of parts are maintained in the track above the delivery point. If the length of the straight inclined portion of the track containing parts is denoted by L_2, the number of parts N_p is given by

$$N_p = \frac{L_2 + R\alpha + L_1}{L} \tag{5.2}$$

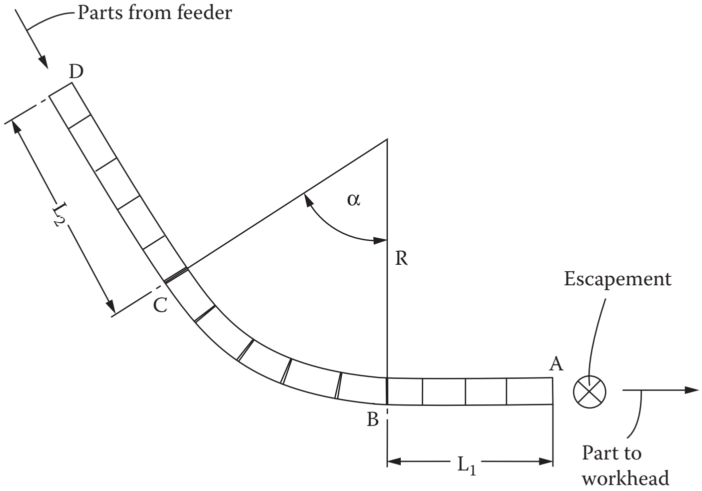


FIGURE 5.2 Idealized horizontal-delivery gravity feed track.

An equation is now derived giving the time t_p to deliver one part of length L. It is assumed in the analysis that the length of each part is small compared to the dimensions of the feed track and that the column of parts can be treated as a continuous, infinitely flexible rod.

When the escapement opens and the restraining force at A is removed, the column of parts starts to slide toward the workhead. In estimating the acceleration a of the column of parts, it is convenient to consider separately the parts in the three sections of the track, AB, BC, and CD, as shown in Figure 5.3.

If the mass per unit length of the column of parts is denoted by m_1, the weight of section AB is given by m_1L_1g. The total frictional resistance in this region is given by $\mu_d m_1 L_1 g$, where μ_d is the coefficient of dynamic friction between the parts and the track.

The equation of motion for section AB is given by

$$F_1 = m_1 L_1 (\mu_d g + a) \tag{5.3}$$

where F_1 is the force exerted on the parts in section AB by the remainder of the parts in the feed track, and a is the initial acceleration of all the parts.

Similarly, the column of parts in the straight inclined portion CD of the feed track is partly restrained by a force F_2, given by

$$F_2 = m_1 L_2 (g \sin \alpha - \mu_d g \cos \alpha - a) \tag{5.4}$$

To analyze the motion of the parts in the curved section BC of the feed track, it is necessary to consider an element of length $Rd\theta$ on a portion of the track that is inclined at an angle θ to the horizontal. In this case, a force F resists the motion

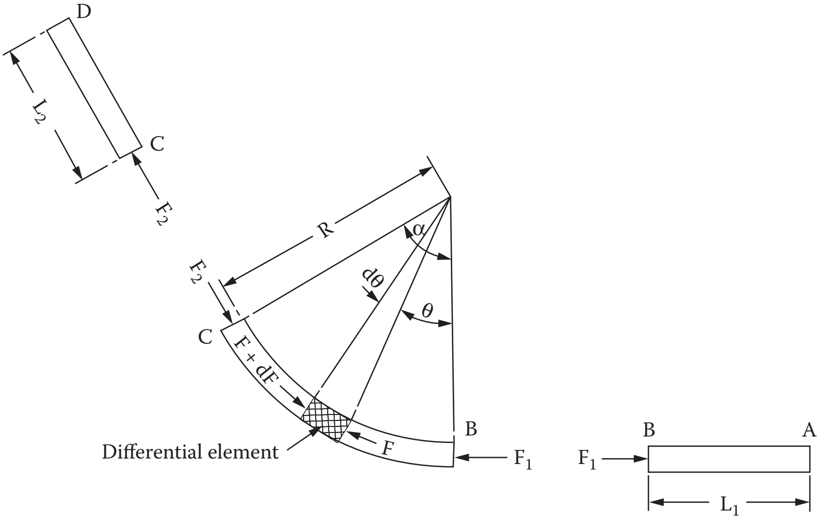


FIGURE 5.3 Three separate sections of the idealized horizontal-delivery track.

of the element, and a force ($F + dF$) tends to accelerate the element. These forces have a small component $Fd\theta$ that increases the reaction between the parts and the track and, consequently, increases the frictional resistance.

The forces acting on the element are shown in Figure 5.4, and the equilibrium equation of forces in the radial direction n is

$$N_1 = m_1\, g\, R \cos\theta\, d\theta + F\, d\theta \tag{5.5}$$

The equation of motion in the tangential direction t is

$$dF + m_1\, g\, R \sin\theta\, d\theta \quad \mu_d N_1 = m_1\, R\, a\, d\theta \tag{5.6}$$

Substituting Equation 5.5 in Equation 5.6 and rearranging the terms, the following first-order linear differential equation with constant coefficients is obtained:

$$\frac{dF}{d\theta} - \mu_d F = m_1 R(a + \mu_d g \cos\theta - g \sin\theta) \tag{5.7}$$

The general solution to Equation 5.7 is

$$F = Ae^{\mu_d \theta} + m_1\, g\, R \left[\frac{(1 - \mu_d^2)\cos\theta + 2\mu_d g \sin\theta}{1 + \mu_d^2} - \frac{a}{\mu_d g} \right] \tag{5.8}$$

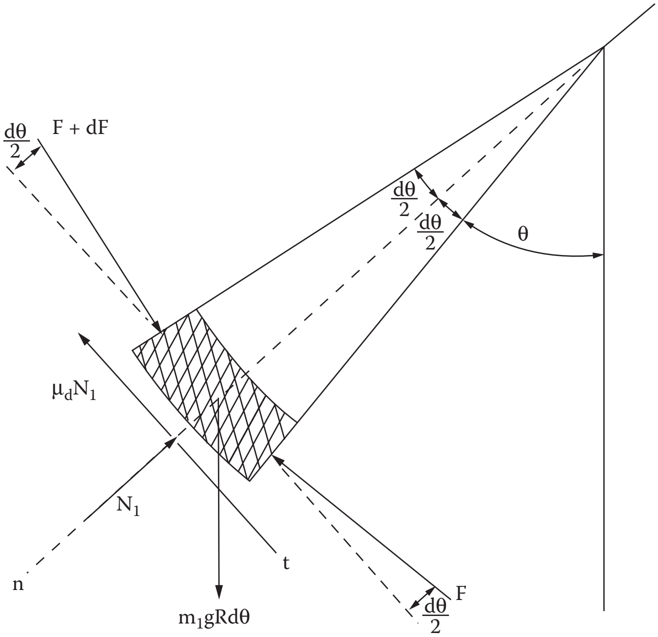


FIGURE 5.4 Free-body diagram for an element.

There are two applicable boundary conditions: $\theta = 0$, $F = F_1$, and $\theta = \alpha$, $F = F_2$. The first boundary condition gives

$$A = F_1 - m_1\,gR\left(\frac{1-\mu_d^2}{1+\mu_d^2} - \frac{a}{\mu_d g}\right) \tag{5.9}$$

where F_1 is given by Equation 5.3.

Equation 5.8 relates the acceleration of the line of parts along the curved and horizontal sections of the track when a force F is applied to the end of the line located at an angle θ. This applied force at the end is F_2, given by Equation 5.4. Using this second boundary condition and solving Equation 5.8 for a/g, we obtain

$$\frac{a}{g} = \frac{\begin{array}{c}(L_2/R)(\sin\alpha - \mu_d\cos\ \alpha) - (L_1/R)\mu_d e^{\mu_d\alpha} \\ +\ \{[(1-\mu_d^2)(e^{\mu_d\alpha} - \cos\alpha) - 2\mu_d\sin\alpha]/(1+\mu_d{}^2)\}\end{array}}{(L_2/R) + (L_1/R)e^{\mu_d\alpha} + (e^{\mu_d\alpha} - 1)/\mu_d} \tag{5.10}$$

Equation 5.10 shows the relationship between the nondimensional acceleration a/g of the entire line of parts and the design parameters L_2/R, L_1/R, α, and

μ_d. Because the part length is small compared to the total length of track, the acceleration is assumed constant during delivery of one part, and thus the time t_p for one part to move into the workhead can be found from the kinematic expression

$$t_p = \left(\frac{2L}{a}\right)^{1/2} \tag{5.11}$$

where L is the length of the part.

Unfortunately, Equation 5.10 is cumbersome to use for calculations and, as a consequence, it is not easy to determine quickly the effect of a design change. It is also unrealistic to graph the information contained in Equation 5.10 because there are five independent nondimensional design parameters. A nomogram would simplify this work, but Equation 5.10 is not in a form suitable for this approach. However, the following method, developed by Murch and described in Reference 1 [1], allows a nomogram to be developed that will give results sufficiently accurate for practical purposes. Equation 5.10 can be approximated as

$$\frac{a}{g} = f_1(\mu_d) + f_2\left(\frac{L_1}{R}\right) + f_3(\alpha) + f_4\left(\frac{L_2}{R}\right) \tag{5.12}$$

which is a summation of independent functions of a single variable and is an acceptable form for a nomogram. The functions are

$$f_1 = 0.94(0.5 - \mu_d) \tag{5.13}$$

$$f_2 = 0.428(L_1/R) \tag{5.14}$$

$$f_3 = 0.0084(\alpha - 45) \tag{5.15}$$

with α expressed in degrees, and

$$\frac{L_2}{R} = \frac{0.31e^{9.66(a/g)}}{1 + 0.018e^{-63(a/g)}} \tag{5.16}$$

Although no explicit function f_4 could be found to satisfy Equation 5.12, a numerical relationship can be developed from Equation 5.16 for producing a nomogram.

Because Equation 5.11 is also in a form suitable for nomographic presentation, the combined nomograms for Equation 5.10 and Equation 5.11 are shown together in one nomogram in Figure 5.5. This nomogram relates all the parameters

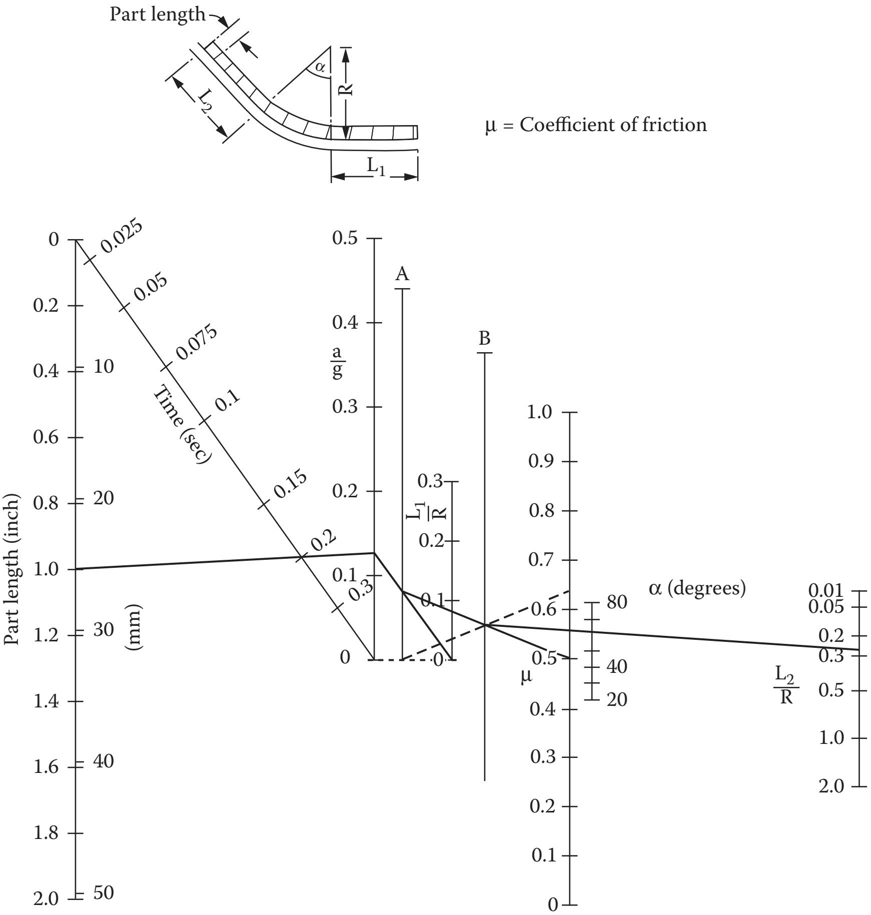


FIGURE 5.5 Nomogram solution to Equation 5.10 and Equation 5.11.

that must be considered for the design of the lower section of a horizontal-delivery gravity feed track.

5.1.2 EXAMPLE

Suppose that a workhead is operating at a rate of 1 assembly/sec and has 0.2 sec to receive a 25-mm part, the value of L_1/R is ordinarily chosen to be as small as possible and, in this situation, equals zero, and the value of the dynamic coefficient of friction is 0.5. What are the values of L_2/R and α that will complete this design?

A line is drawn on the nomogram (see Figure 5.5) from a value of part length of 25 mm (1 in.) through a value of time of 0.2 sec, intersecting the a/g line at a value of 0.13. A second line is drawn from this value of a/g to a value of zero on the L_1/R scale. This line intersects the turning line A. A third line, drawn from the turning line *A* to a value of 0.5 on the μ scale, intersects the turning line *B*. The last line is drawn from this intersection of the turning line *B* through the α and the L_2/R scales. A number of solutions are possible; one such solution gives values of α and L_2/R of 60° and 0.27, respectively. Substitution of these design parameters back into Equation 5.10 yields a value of 0.12 for a/g. The subsequent time from Equation 5.11 is 0.207 sec, which, compared with the system design specification of 0.2 sec, is less than a 4% error.

Several comparisons were made to check the accuracy of this nomogram, and the results showed that this nomogram was significantly accurate for design work. It is reasonable to expect the nondimensional acceleration found using this nomogram to be correct within 0.03. The worst results occur with small angles and large values of L_2/R or large coefficients of friction, but these situations are ordinarily avoided in practice.

It is interesting to note the effect of the value of the coefficient of friction on the value of the nondimensional acceleration a/g. From Equation 5.12 and Equation 5.13, it is clear that an error in the value of the coefficient of friction produces a similar error in the value of a/g. Apparently, the source of the greatest error in this work is in the estimation of the value of the coefficient of friction. Some typical values are given in Table 5.1. A simple method for determining the coefficient of dynamic friction has also been developed, which has the advantage of using the actual parts in the experiments. The details are presented in Appendix A.

It has been tacitly assumed that the static friction would not affect this dynamic analysis. If the value of the coefficient of static friction μ_s is significantly large, however, the parts in the queue simply will not move. This occurs if the numerator in Equation 5.10 is less than or equal to zero when the value of the angle α is greater than arctan μ_s. For this calculation, the value of the coefficient of static friction is substituted for the coefficient of dynamic friction μ_d. Using the design parameters $L_1/R = 0$, $L_2/R = 0.27$, and $\alpha = 60°$, the nondimensional

TABLE 5.1
Coefficient of Dynamic Friction of a Variety of Part and Track Material Combinations

	Track					
Part	**Nylon**	**Plexiglas**	**Brass**	**Aluminum**	**Cast Iron**	**Steel**
Nylon	0.520	0.536	0.568	0.475	0.375	0.503
Plexiglas	0.502	0.473	0.537	0.503	0.411	0.425
Brass	0.354	0.425	0.370	0.345	0.216	0.250
Aluminum	0.416	0.458	0.437	0.374	0.304	0.327
Cast iron	0.314	0.370	0.368	0.268	0.218	0.252
Steel	0.349	0.419	0.432	0.353	0.273	0.306

acceleration from Equation 5.10 equals zero when the value of the coefficient of static friction is less than this value.

Fortunately, the nomogram can also be used for this static analysis. A line drawn between $a/g = 0$ and L_1/R intersects the turning line A. A line drawn from this intersection through the previous intersection of turning line B crosses the μ line at the critical value of μ_s. Dashed lines are used on Figure 5.5 to show this procedure for the preceding example.

5.1.3 ON/OFF SENSORS

On automatic assembly machines, it is essential to maintain a supply of correctly oriented parts to the workhead. A workhead that is prepared to carry out the assembly operation but is awaiting the part to be assembled represents downtime for the whole assembly line. Thus, for obvious economic reasons, correctly oriented parts should always be available at each station on an assembly machine. The probability that a part will be available at a workhead is called the *reliability of feeding* and should not be confused with the problems associated with defective parts, which may jam in the feeding device or workhead and thus affect the reliability of the complete system. The latter subject is discussed in detail in a later chapter.

When automatic feeding devices are used on assembly machines, the mean feed rate is usually set higher than the assembly rate to ensure a continuous supply of parts at the workhead. Under these circumstances, the feed tracks become full, and parts back up to the feeder. For vibratory-bowl feeders, however, this method is not always satisfactory. With these feeders, the parts in the line in the feed track are usually prevented by a pressure brake from interfering with the orienting devices mounted on the bowl-feeder track. If a part filters past the orienting devices and arrives at the pressure break when the delivery chute is full, it is rejected back into the bowl. If this occurs too frequently, excessive wear to both the bowl and the parts can result.

To solve the problems caused by overfeeding and, consequently, ease the problem of wear, a simple control system can be employed that incorporates sensing devices located at two positions on the feed track. The feeder is turned on when the level of the parts falls below the sensing device nearest the workhead. The feeder is still set to deliver oriented parts at a higher rate than required, and the parts gradually fill the delivery chute and back up to, and then past, the level of the first sensing device. When the second sensing device, which is located near the feeder, is activated, the bowl is turned off, and the level of the parts starts to fall again. When the level of the parts falls below the level of the first sensing device, the first device is activated, and the bowl feeder is again set in motion. Because the output of the bowl is a random variable, there may be a time delay before an oriented part leaves the bowl. Thus, it is possible that the entire line of parts between the lower sensor and the critical level found from Equation 5.10 will be used by the workhead before an oriented part arrives from the feeder.

This situation has been studied theoretically [2] to provide the designer of assembly machines with the information necessary to position the sensing devices in the feed track so that the probability of the workhead being starved of parts is kept within acceptable limits.

5.1.3.1 Theory

Most vibratory feeders are fitted with an orienting system that reorients or rejects those parts that would otherwise be fed incorrectly oriented. It is assumed that, without the orienting system and for a particular setting, a vibratory-bowl feeder would deliver n_f parts during the period of one workhead cycle. Thus, if η is the proportion of parts that pass through the orienting system, $n_f\eta$ is the average number of parts that pass into the feed track during each workhead cycle. The factor η can be regarded as the efficiency of the orienting system, as discussed in Chapter 3.

The output from the bowl feeder is assumed to have a binominal distribution with a mean of $n_f\eta$ and a variance of $n_f\eta(1 - \eta)$ for each workhead cycle. For large values of n_f, a binomial distribution can be closely approximated by a normal distribution of the same mean and variance. The approximation improves an n_f increases but is always quite good if η is neither close to zero nor close to unity. Thus, the output from the feeder is approximately normal $[n_f\eta, n_f\eta(1 - \eta)]$ for every time span of one workhead cycle. The value of $n_f\eta$ must be greater than unity if the average value of the queue length is to increase. In ordinary steady-state queuing theory, $n_f\eta$ is termed the *traffic density* and is less than unity. For this reason, the results of steady-state queuing theory cannot be applied to this problem.

Referring to Figure 5.6, N_b is the number of parts that can be held in the feed track between the lowest acceptable line level and the first sensing device. Thus, if t_w is the cycle time of the workhead, the distribution of parts that build up the line in N_bt_w seconds is approximately normal $[N_b(n_f\eta - 1), N_bn_f\eta(1 - \eta)]$, where N_b is subtracted from the mean to allow for the N_b parts that are assembled in N_bt_w seconds.

Figure 5.7 shows the density function, for a particular value of N_b, for the net number of parts that build up the line in N_bt_w seconds. The value of N_b corresponds to a particular reliability r, which means that the workhead will be starved of parts for only 100 $(1 - r)$% of the time following an activation of the on sensor. The area under the density function in Figure 5.7 equals r. An increase or decrease in N_b changes the mean $[N_b(n_f\eta - 1)]$ more than it changes the standard deviation $[N_bn_f\eta(1 - \eta)]^{1/2}$. Thus, the smaller the value of N_b, the smaller the area r under the density function and the lower the reliability.

Because the area under the curve in Figure 5.7 is r, the average number of parts to leave the bowl feeder $(N_bn_f\eta)$ is equal to n_s standard deviations, i.e., $n_s[N_bn_f\eta(1 - \eta)]^{1/2}$, where n_s is determined from a normal distribution table. Thus,

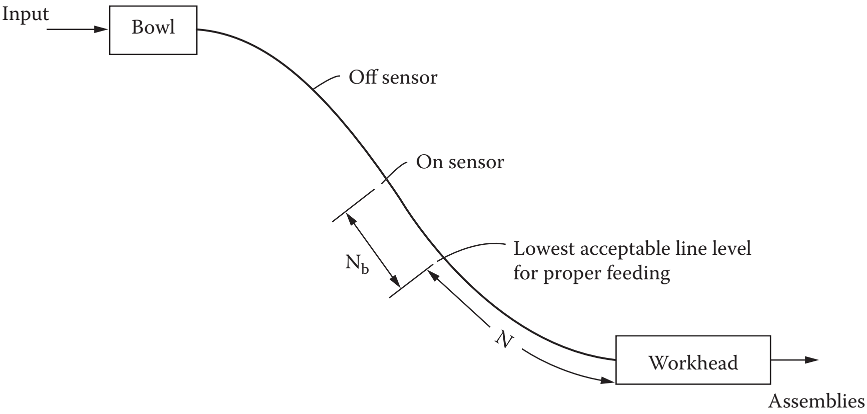


FIGURE 5.6 Gravity feed track with on/off sensors.

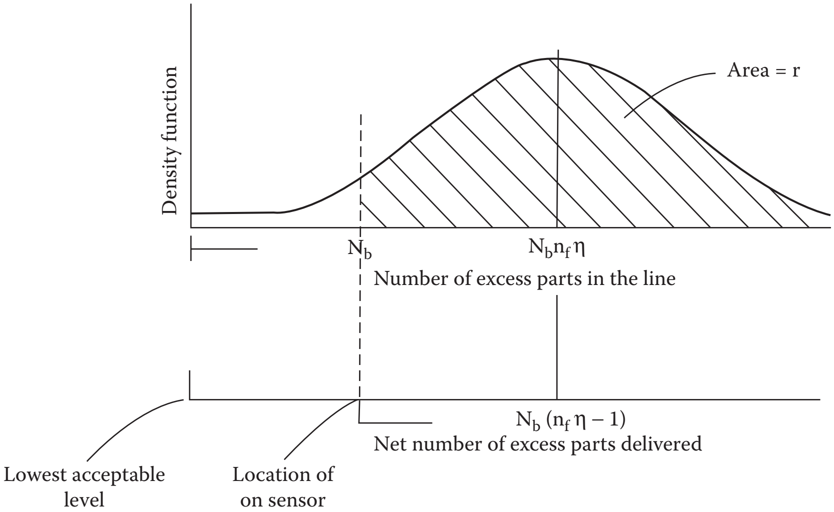


FIGURE 5.7 Density functions for delivered parts. (From Murch, L.E. and Boothroyd, G., On-Off Control of Parts Feeding, *Automation*, Vol. 18, August 1970, pp. 32–34. With permission.)

$$N_b = \frac{n_s^2(1-\eta)}{n_f \eta} \tag{5.17}$$

For example, for a reliability of 0.99997 ($n_s = 4$),

$$N_b = \frac{16(1-\eta)}{n_f\eta} \tag{5.18}$$

where $n_f\eta$ and η are known parameters for the bowl feeder.

In cases in which these parameters are unknown, it may be convenient to let $N_b = n_s^2$, which is its maximum value because η is always positive and $n_f\eta$ must always be set greater than unity.

It has been stated that, for a binomial distribution to be closely approximated by a normal distribution, n_f should be large. To determine a satisfactory value for n_f for particular values of η and r, a computer simulation routine was developed. Table 5.2 shows some of the results from this simulation for $r = 0.99997$. For relatively large values of η, the corresponding values of $n_f\eta$ may be too large to be of any practical interest. However, when the theoretical value of N_b was increased by 2, the same simulation yielded the results shown in Table 5.3. Thus, for $n_f\eta \geqslant 1.6$ (with $r = 0.9997$),

$$N_b = \frac{16(1-\eta)}{n_f\eta} + 2 \tag{5.19}$$

Equation 5.19 can be used to estimate the number of parts between the lower sensor and the level of parts for acceptable operation when the feeder is capable of delivering at a rate 60% greater than the workhead assembly rate, a situation that is not uncommon when on/off sensors are employed. An examination of Equation 5.19 indicates that the maximum value of N_b is 12. This occurs when η is small and $n_f\eta$ equals 1.6, its minimum. Other conditions that satisfy the constraint on Equation 5.19 will always produce results for N_b less than or equal to 12. Thus, when little is known about a feeder except that it significantly overfeeds, the lower sensor can be placed in a position in which N_b equals 12 and satisfactory performance is assured.

TABLE 5.2
Simulation Results for Equation 5.18; $r = 0.99997$

η	n_f	$n_f\eta$
0.2	10	2
0.5	4	2
0.8	20	16

TABLE 5.3
Simulation Results for Equation 5.19; $r = 0.99997$

η	n_f	$n_f\eta$
0.1	16	1.6
0.2	8	1.6
0.5	3	1.5
0.8	2	1.6

The number of parts that can be held between sensing devices has no effect on the average running time of the feeder but does affect the average frequency of activations of the sensing devices.

Often, only one sensor is used. Besides activating the feeder, it activates a time delay to simulate the second sensor. Several types of sensors, including fiber optics or pneumatics, can be used on the track, but the basic logical circuitry governing their operation is identical.

5.1.4 FEED TRACK SECTION

A compromise is necessary when designing the feed track section. The clearances between the part and the track must be sufficiently large to allow transfer and yet small enough to keep the part from losing its orientation during transfer. In the curved portions of the track, further allowances have to be made to prevent the part from jamming. Figure 5.8 shows a cylindrical part in a curved tubular track. For the part to negotiate the bend, the minimum track diameter d_t is given by

$$d_t = c + D \tag{5.20}$$

and by geometry,

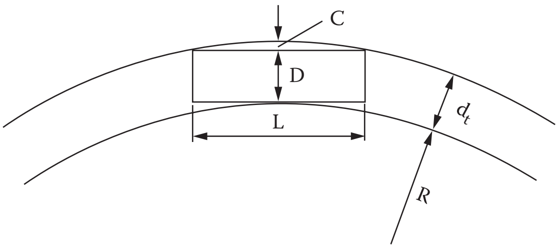


FIGURE 5.8 Construction to determine minimum diameter of a curved feed track.

$$(R + d_t - c)^2 + \left(\frac{L}{2}\right)^2 = (R + d_t)^2$$

or

$$2c(R + d_t) - c^2 = \left(\frac{L}{2}\right)^2 \tag{5.21}$$

where R is the inside radius of the curved track and L the length of the part. If c is small compared with $2(R + d_t)$, this expression becomes approximately

$$2c(R + d_t) = \left(\frac{L}{2}\right)^2 \tag{5.22}$$

Substituting for c from Equation 5.20 into Equation 5.22 and rearranging, we obtain

$$d_t = 0.5\left\{\left[(R + D)^2 + \frac{L^2}{2}\right]^{1/2} - (R - D)\right\} \tag{5.23}$$

If the parts are sufficiently bent or bowed, it may be difficult to design a curved track that will not allow overlapping of parts and consequent jamming. This is illustrated in Figure 5.9.

Figure 5.10 illustrates typical track sections used for transferring cylinders, flat plates, and headed parts. An important point to be remembered when designing a feed track is that the effective coefficient of friction between the parts and the track may be higher than the actual coefficient of friction between the two

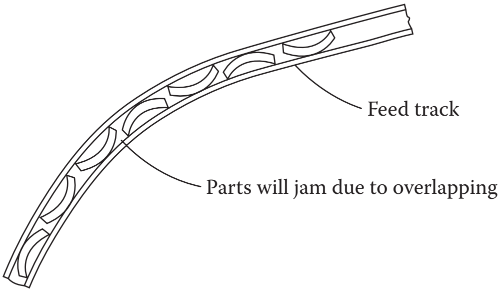


FIGURE 5.9 Blockage in a curved feed track.

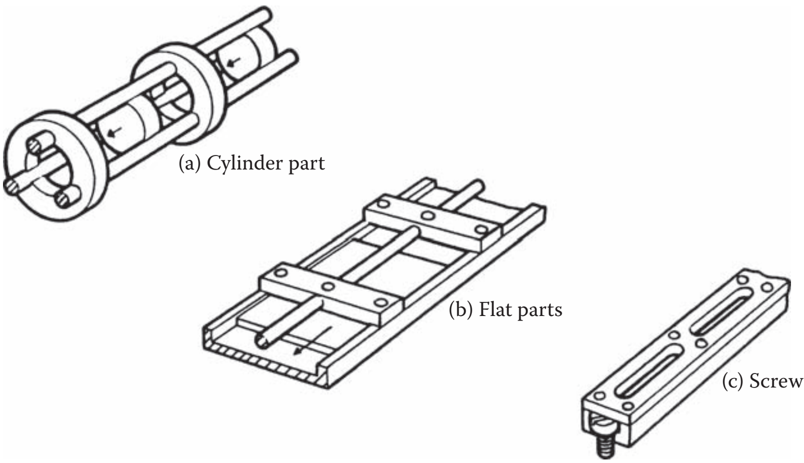
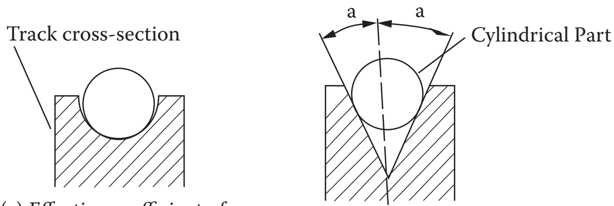


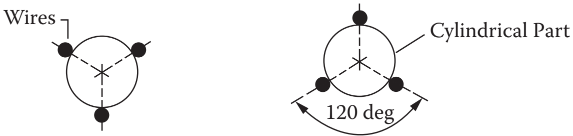
FIGURE 5.10 Various gravity feed track sections for typical parts.

materials. Figure 5.11 gives some examples of the effect of the track cross section on the effective coefficient of friction. The increase of 100% in friction given by the example in Figure 5.11d could have very serious consequences in a gravity-feed system. It is also important to design these tracks with removable covers or access holes for the quick removal of jammed parts.



(a) Effective coefficient of fricion equal to actual coefficient of friction ($\mu = \mu_d$)

(b) Effective coefficient of fricion equal to actual coefficient of friction $\left(\mu = \dfrac{\mu_d}{\sin a}\right)$



(c) Effective coefficient of fricion equal to actual coefficient of friction ($\mu = \mu_d$)

(d) Effective coefficient of friction twice the actual coefficient of friction $\mu = 2\mu_d$

FIGURE 5.11 Relation between effective coefficient of friction μ and actual coefficient of friction μ_d for various track designs.

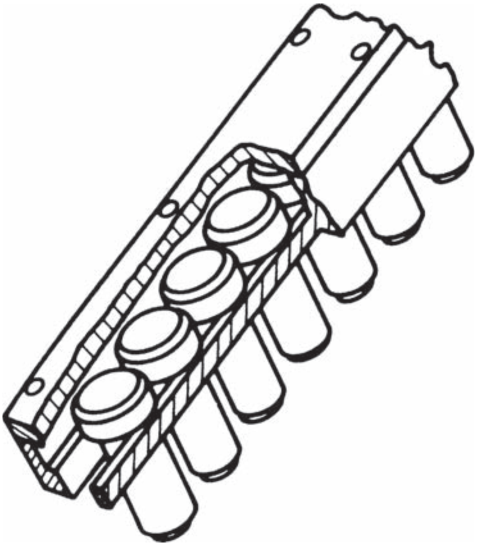


FIGURE 5.12 Headed parts in a gravity feed track.

5.1.5 DESIGN OF GRAVITY FEED TRACKS FOR HEADED PARTS

Of the many parts that can be fed into a gravity feed track, perhaps the most common are headed parts such as screws and rivets, which are often fed in the manner shown in Figure 5.12. Clearly, if the track inclination is too small or if the clearance above the head is too small, the parts will not slide down the track. It is not always understood, however, that the parts may not feed satisfactorily if the track has too steep an inclination or if too large a clearance is provided between the head of the part and the track. Also, under certain circumstances, a part may not feed satisfactorily, whatever the inclination or clearance. This analysis of the design of gravity feed tracks for headed parts provides the designer of assembly machines and feeding devices with the information necessary to avoid situations in which difficulty in feeding will occur.

5.1.5.1 Analysis

Figure 5.13 shows a typical headed part (a cap screw with a hexagon socket) in a feed track. It is clear that as the track inclination θ is gradually increased and provided that the corner *B* of the screw head has not contacted the lower surface of the cover of the track, the screw will slide when $\theta > \arctan \mu_1$, where μ_1 is a function of the coefficient of static friction between the screw and the track. On further increase in the track inclination, the condition shown in Figure 5.14 will eventually arise when the corner *B* of the screw head has just made contact with the lower surface of the cover of the track. Immediately prior to this condition, the center of mass of the screw lies directly below *AA*, a line joining the points of contact between the screw head and the track. From Figure 5.14, it can be seen that z, the distance from the line *AA* to the axis of the screw, is given by

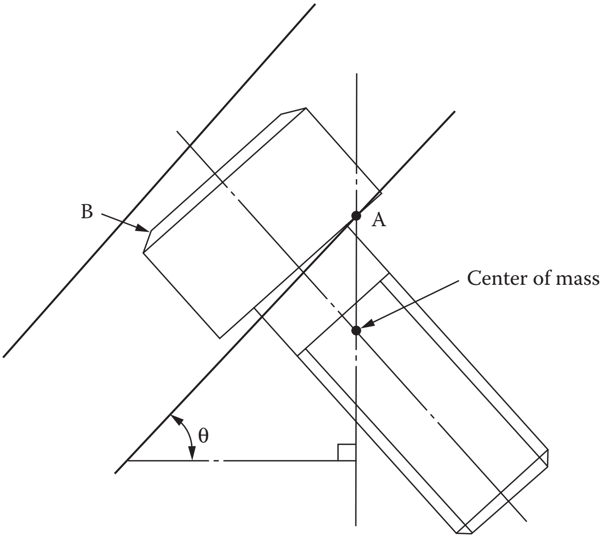


FIGURE 5.13 Position of a headed part that does not touch the track cover.

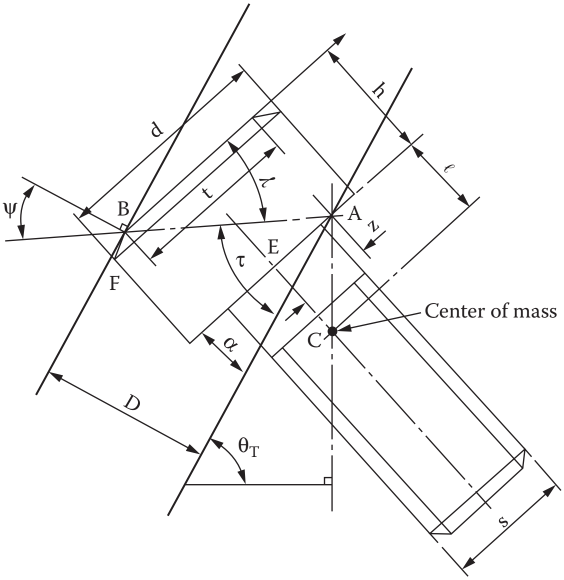


FIGURE 5.14 Position of a headed part when corner *B* just contacts the lower surface of the track cover.

$$z^2 = \frac{d^2 - s^2}{4} \tag{5.24}$$

where s is the width of the slot and the diameter of the shank, and d is the diameter of the screw head.

Also, from the triangle ACE (see Figure 5.14),

$$\frac{z}{\ell} = \tan\ (\theta_T - \alpha) \tag{5.25}$$

where ℓ is the distance from the center of mass of the screw to a plane containing the underside of the head, α is the angle between the screw axis and a line normal to the track, and θ_T, which is called the *tilt angle*, is the track angle at which the top of the screw head just contacts the lower surface of the top cover of the track. From Figure 5.14,

$$\alpha = \tau - \gamma \tag{5.26}$$

where

$$\tau = \arcsin \frac{D}{[h^2 + (t/2 + z)^2]^{1/2}} \tag{5.27}$$

and

$$\gamma = \arctan \left(\frac{h}{t/2 + z} \right) \tag{5.28}$$

where D is the depth of the track, h the depth of the screw head, and t the diameter of the top of the screw head. Thus, combining Equation 5.26–Equation 5.28, we obtain

$$\theta_T = \arctan\left(\frac{z}{\ell}\right) - \arctan\left(\frac{h}{t/2 + z}\right) + \arcsin\left(\frac{D}{[h^2 + (t/2 + z)^2]^{1/2}}\right) \tag{5.29}$$

Sliding will always occur if $\theta_T > \theta > \arctan \mu_1$ because, under these circumstances, the track angle is greater than the angle of friction, and there is no contact between the top of the screw head and the track cover. However, sliding may still occur if θ is larger than θ_T. This situation is shown in Figure 5.15, where it can be seen that a frictional force occurs between the screw head and the track cover as well as on the lower portion of the track.

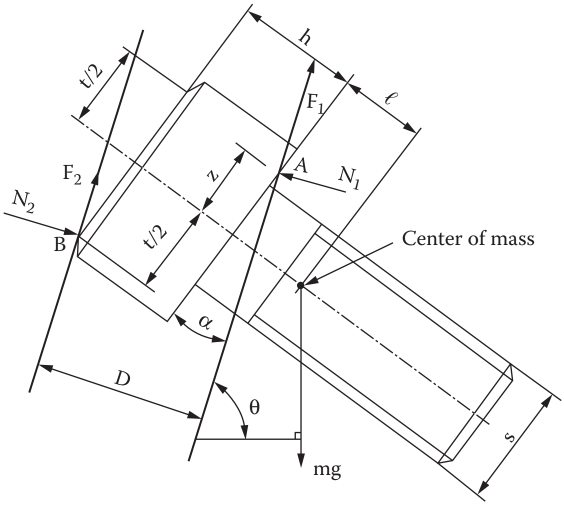


FIGURE 5.15 Forces acting on a cap screw in a feed track.

For sliding to occur under these conditions,

$$mg \sin \theta > F_1 + F_2 \tag{5.30}$$

where

$$F_1 = \mu_1 N_1$$

and (5.31)

$$F_2 = \mu_2 N_2$$

where μ_1 and μ_2 are the effective values of the coefficient of static friction between the part and the track at A and B, respectively (see Figure 5.15). Resolving forces normal to the track gives

$$N_1 = N_2 + mg \cos \theta \tag{5.32}$$

and taking moments about A gives

$$mg[\ell \sin (\theta - \alpha) - z \cos (\theta - \alpha)] \tag{5.33}$$

$$= N_2 \left[\left(\frac{t}{2} + z \right) \cos \alpha - h \sin \alpha \right] + F_2 D$$

Substituting Equation 5.31 to Equation 5.33 in Equation 5.30 and rearranging the terms, we get

$$\sin\theta > \mu_1 \cos\theta + (\mu_1 + \mu_2)\frac{\ell \sin(\theta - \alpha) - z\cos(\theta - \alpha)}{[(t/2 + z)\cos\alpha - h\sin\alpha - \mu_2 D]} \tag{5.34}$$

where μ_1 is the effective coefficient of friction between the screw head and the bottom portion of the track, and μ_2 is the effective coefficient of friction between the screw head and the track cover.

Under the conditions shown in Figure 5.13–Figure 5.15, a portion of the screw head lies below the lower contact surface of the track, and the effective coefficient of static friction between the screw and the track is greater than the actual coefficient of static friction μ_s for the two materials. It can be shown that, for this situation, the relation between μ_s and μ_1 is given by

$$\mu_1 = \mu_s \square\square \left[\left(d \sin\frac{\alpha}{2z} \right)^2 \square + \cos^2\alpha \right]^{1/2} \tag{5.35}$$

In this particular case, the difference between μ_s and μ_1 is small, but in some cases discussed later in this section, this effect is of importance. Because there is point contact between the track cover and the screw head, $\mu_2 = \mu_s$.

Thus, at least two conditions govern the motion of the screw in the track. First, if the track angle is greater than the angle of friction and is less than or equal to the tilt angle θ_T, the screw slides. Under these circumstances, the greater the tilt angle θ_T, the larger the range of values of μ_s for which the screw slides. Therefore, as can be seen from Equation 5.29, the value of D, the track depth, should be as large as possible.

Second, the maximum track angle is restricted to the value given by Equation 5.34 and, in this case, again, the greater the depth of the track, the greater this maximum value θ. It is of interest now to determine the critical value of track depth below which a screw cannot jam in the track, because this will allow a complete definition of the range of track angles and track depths for which a part will feed satisfactorily.

If the track depth D is gradually increased, a special case of the condition shown in Figure 5.15 will eventually arise. This occurs when the angle between a line joining A and B and a line normal to the track becomes equal to the angle of friction between the screw and the track. For larger values of D, the part will not normally make contact with the upper portion of the track. Under these circumstances, however, the screw will jam in the track if it makes contact across A and B. Thus, the situation arises in which, theoretically, the screw should slide but, if a small perturbation rotates it sufficiently to contact the cover, the screw will lock in the track. This possibility should clearly be avoided in practice. From the geometry of Figure 5.15, the maximum value of D is thus given by

$$D_{\max} = [h^2 + \left(\frac{t}{2} + z\right)^2 \cos\beta_2]^{1/2} \tag{5.36}$$

where $\tan\beta_2 = \mu_2 = \mu_s$.

Figure 5.16 shows a graph of θ plotted versus D/h for a size-8 hexagon socket-type cap screw, where $d = 1.712s$, $h = s$, $\ell = 1.5s$, and $t = 1.42s$.

Although, in practice, the width of the track s would be larger than the diameter of the screw shank, it should be as small as possible, and in all the examples dealt with in this section, it is considered to be equal to the shank diameter.

The results in Figure 5.16 show, for various values of μ_s, the ranges of values θ and D/h for which the screw will slide down the track without the possibility of jamming. It can be seen that as the coefficient of friction is increased, the ranges of values of θ and D for feeding to occur decrease. It should also be noted that the line XX, representing the tilt angle θ_T, passes through the points that give (1) the minimum track angle and minimum track depth and (2) the maximum track angle and maximum track depth.

It is now suggested that a reasonable criterion for the best track inclination and track depth would be one in which these parameters are such that feeding would occur for the widest range of values of μ_s. This condition occurs when the points defined under (1) and (2) in the preceding paragraph become identical. Referring to Figure 5.16, this condition occurs when $\theta_{\max} = \theta_{\min}$ and $D_{\max} = D_{\min}$, that is, when $\theta = 39°$ and $D/h = 1.32$, and, for this situation, it can be seen that the screw will always slide if $\mu_s < 0.81$.

Now, $\theta_{\min}$ occurs when $\theta_T = \beta_1$. Substituting this in Equation 5.25 gives

$$\tan(\beta_1 - \alpha) = \frac{z}{\ell}$$

or

$$\beta_1 - \alpha = \arctan\left(\frac{z}{\ell}\right) \tag{5.37}$$

When θ equals $\theta_{\max}$, it also equals θ_T; hence, from Figure 5.14, the value of $\theta_{\max}$ occurs when ψ equals β_2, which gives

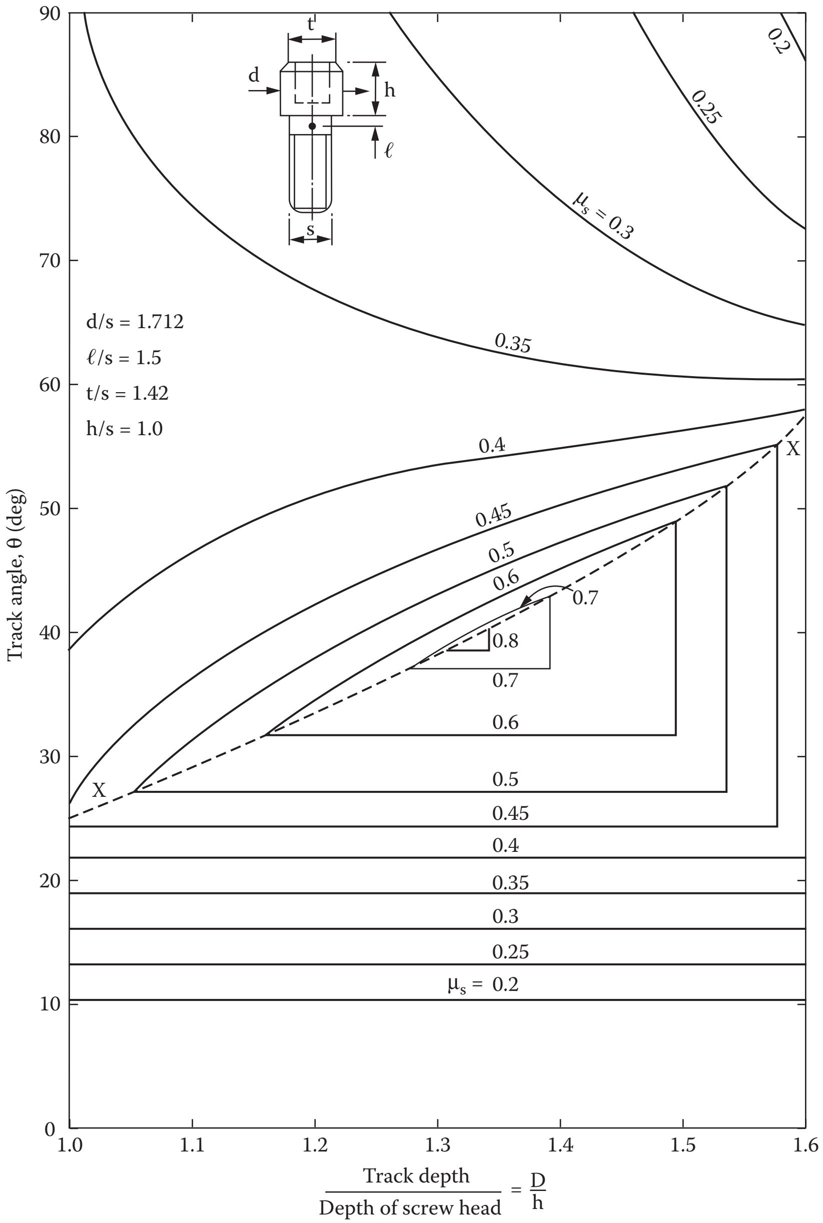


FIGURE 5.16 Conditions for which a particular screw will slide in a gravity feed track. (From Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101. With permission.)

$$\tan(\alpha + \beta_2) = \frac{z + t/2}{h}$$

or

$$\alpha + \beta_2 = \arctan\left(\frac{z + t/2}{h}\right) \tag{5.38}$$

The relationships among β_1, β_2, and β are given by

$$\tan\beta_1 = \tan\left[\left(\frac{d\sin\alpha}{2z}\right)^2 + \cos^2\alpha\right] \tag{5.39}$$

and

$$\beta_2 = \beta \tag{5.40}$$

Solving Equation 5.37 to Equation 5.40 simultaneously gives the maximum angle of friction β for which the screw will slide without the possibility of jamming. Substitution of this value in Equation 5.39 and Equation 5.36 gives the corresponding optimum values of the track inclination θ (= β_1) and the track depth D.

The equations necessary to determine the maximum coefficient of friction μ_{max}(= tan β), the track inclination, and the track depth for the proposed optimum conditions for the following four common types of screws have been developed [3]:

1. A cap-head screw of hexagon socket type
2. A flat-head cap or machine screw in a V track
3. A flat-head cap or machine screw in a plain track
4. A button-head cap or round-head machine screw

In all cases, it has been assumed that the width of the slot in the track is equal to the diameter of the screw shank.

5.1.5.2 Results

Graphs of μ_{max}, D/h, and θ vs. ℓ/s for the four types of screws studied are shown in Figure 5.17–Figure 5.20. Each figure shows these values for the two extreme geometries of the particular type of screw. For example, in the case of a cap-head screw of the hexagon socket type, regardless of its size, all values of d/s and t/s fall within the ranges 1.33–1.712 and 1.041–1.42, respectively.

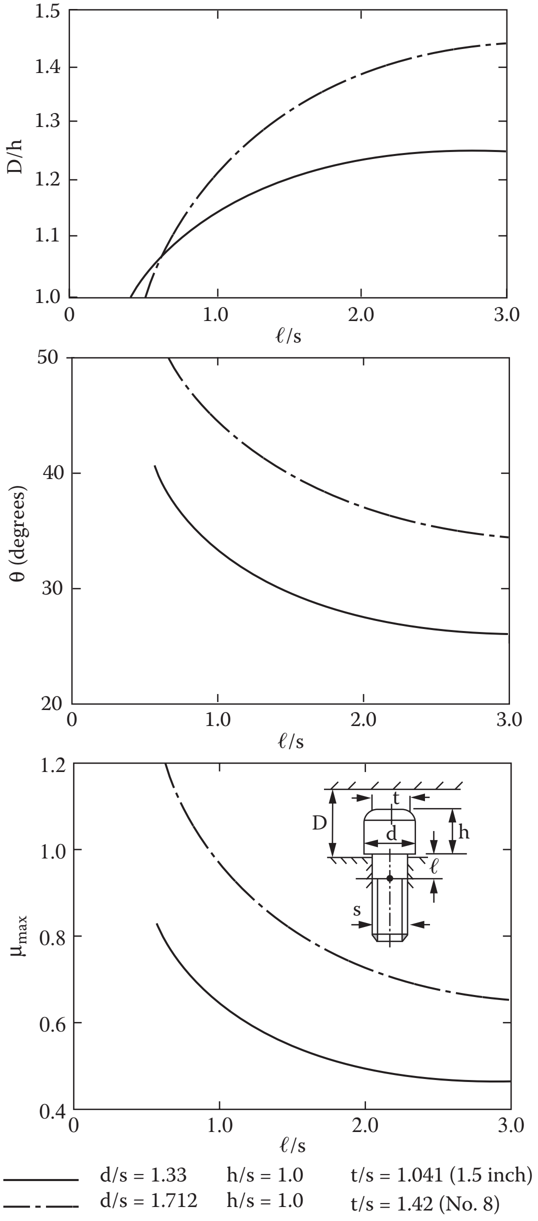


FIGURE 5.17 Optimum values of track angle θ and track depth D for maximum coefficient of friction μ_{max} for cap-head or hexagon-socket screws. (From Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101. With permission.)

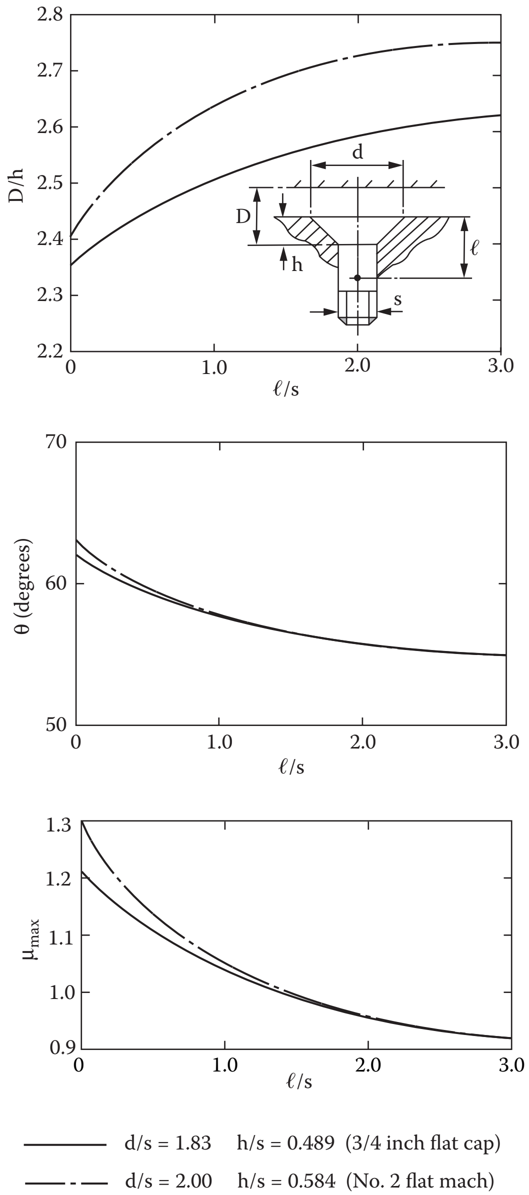


FIGURE 5.18 Optimum values of track angle θ and track depth *D* for maximum coefficient of friction μ_{max} for flat-head cap or machine screws in V track. (From Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101. With permission.)

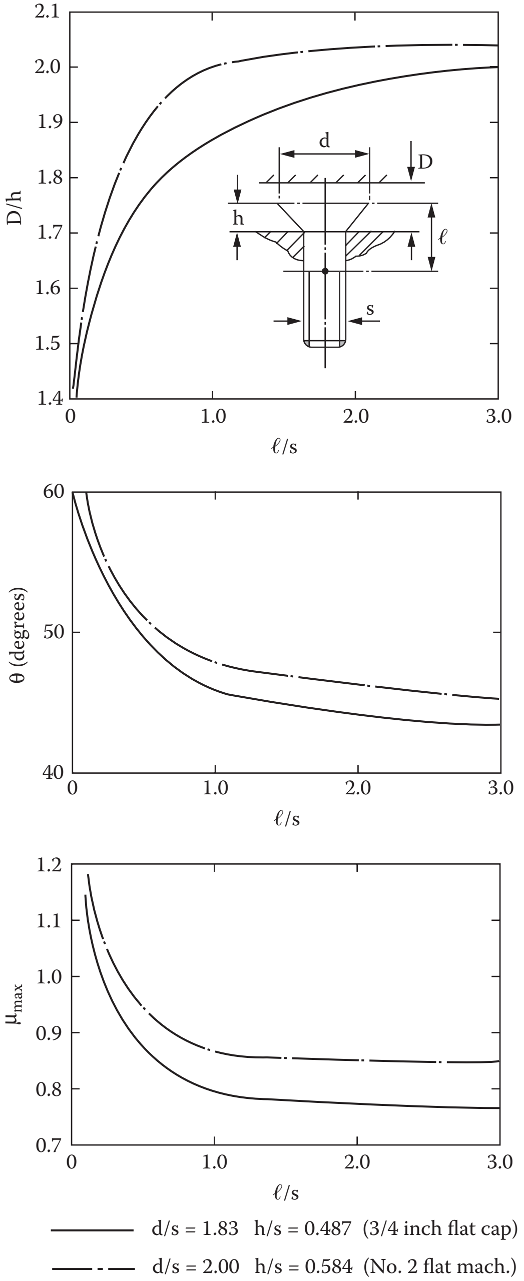


FIGURE 5.19 Optimal values of track angle θ and track depth *D* for maximum coefficient of friction μ_{max} for flat-head cap or machine screws in plain track. (From Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101. With permission.)

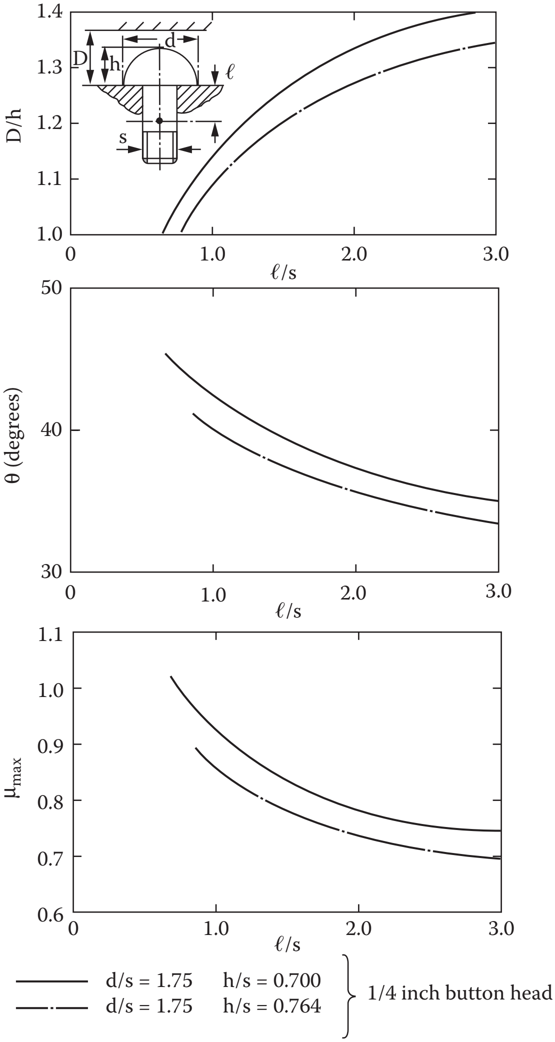


FIGURE 5.20 Optimal value of track angle θ and track depth *D* for maximum coefficient of friction μ_{max} for button-head cap or round-head machine screws. (From Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101. With permission.)

Clearly, the value of (D/h) cannot be less than unity, and thus for some types of screws, it can be seen from these figures that there is a minimum value of ℓ/s for which the analysis is valid. If ℓ/s is less than this minimum value, the parts can be fed into a track with a small clearance, and the only restriction on the track angle is that it must be greater than the effective angle of friction.

Although in practice, there will often be no choice as to the type of screw to be used, it is of interest to note the degree of difficulty in feeding equivalent sizes of the various screws analyzed. For a given length of screw, the most difficult to feed are the larger sizes of cap-head screws of the hexagon socket type and, in this case, if μ_s is 0.5, it would be very difficult to feed the screw if its length were greater than five times its diameter. The easiest screws to feed are the flat-head cap or machine screws and, of the two alternative track designs examined, the V track has better feeding characteristics.

One general point is that, in many cases, the optimum track depth is very much larger than would normally be used in practice and, when the track depth is only slightly larger than the depth of the head, difficulty is often encountered in feeding these parts.

5.1.5.3 Procedure for Use of Figure 5.17 to Figure 5.20

The first step in using the data provided in these figures is to determine the value of ℓ/s for the screw under consideration. The simplest way is to balance the screw on a knife edge and measure the distance ℓ from the center of mass to the underside or top of the screw head, whichever is appropriate. This value is then divided by the shank diameter to obtain the ratio ℓ/s.

The optimum values of the track angle θ and the ratio of track depth to screw-head depth are then read off the appropriate curves in the figures. In all cases except the cap-head screw of the hexagon socket type (Figure 5.17), the ranges of these values are quite small. When using this figure, therefore, it should be remembered that the lower line is for the large sizes and the upper line is for the small sizes.

Finally, reference to the lower graph in Figure 5.17 to Figure 5.20 will give the maximum permissible value of μ_s. If the actual value of μ_s is greater than this, the screw cannot be fed in a slotted gravity feed track.

Although the gravity feed track is the simplest form of feed track, it has some disadvantages. The main disadvantage is the need to have the feeder in an elevated position. This may cause trouble in loading the feeder and in freeing any blockages that may occur. In such cases, the use of a powered track may be considered.

5.2 POWERED FEED TRACKS

The most common types of powered feed tracks are vibratory tracks and air-assisted tracks. A vibratory feed track, illustrated in Figure 5.21, operates on the same principle as a vibratory-bowl feeder (Chapter 3). With this device, the track is generally horizontal, and its performance is subject to many of the limitations of conventional vibratory-bowl feeders. In the feeder shown, the vibrations normal and parallel to the track are in phase, and the feeding characteristics will be affected by changes in the effective coefficient of friction μ between the parts and the track. This was illustrated in Chapter 3, where it was shown that an increase in μ generally gives an increase in the conveying velocity. For example, a typical operating condition occurs when the normal track acceleration A_n = $1.1g_n$. In this case, stable feeding takes place, and Figure 3.8 shows that a change

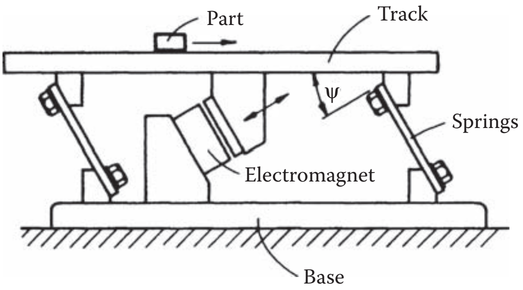


FIGURE 5.21 Horizontal vibratory feed track.

in μ from 0.2 to 0.8 increases conveying velocity from 18 to 55 mm/sec when operating at a frequency of 60 Hz. It is shown in Appendix B that introducing the appropriate phase difference between the components of vibration normal and parallel to the track can give conditions in which the conveying velocity is consistently high for a wide range of values of μ. With a track inclined at 4° (0.07 rad) to the horizontal (a typical figure for a bowl feeder), the optimum phase angle for a normal track acceleration of 1.2 g is approximately 65° (1.1 rad). Figure B.2 shows that this optimum value is not significantly affected by the vibration angle employed. In the work that led to these results, it was also found that the optimum phase angle reduces as the track angle is reduced until, when the track is inclined downward at an angle of 8° (0.14 rad), the optimum phase angle is almost zero. This means that a drive of the type shown in Figure 5.21 operates under almost optimum conditions for a track inclined at 8° downward. Under these circumstances, it is found that the mean conveying velocity for a wide range of μ is given by

$$v_m = 4500/f \tag{5.41}$$

in units of mm/sec, where f is the frequency of vibration in Hertz when the vibration angle is 20° (0.35 rad) and $A_n/g_n = 1.2$. In this case, the mean conveying velocity for an operating frequency of 60 Hz would be 75 mm/sec. A higher feed rate could be obtained by reducing the vibration angle, increasing the downward slope of the track, or reducing the frequency of vibration.

For downward-sloping tracks with a large inclination, large feed rates can be obtained with zero vibration angle. In this case, the track is simply vibrated parallel to itself, and the typical feed characteristics thus obtained are illustrated in Figure 5.22, which shows the effect of parallel track acceleration on the mean conveying velocity for various track angles when the coefficient of friction is 0.5. The results for a feed track with parallel vibration can be summarized by the empirical equation

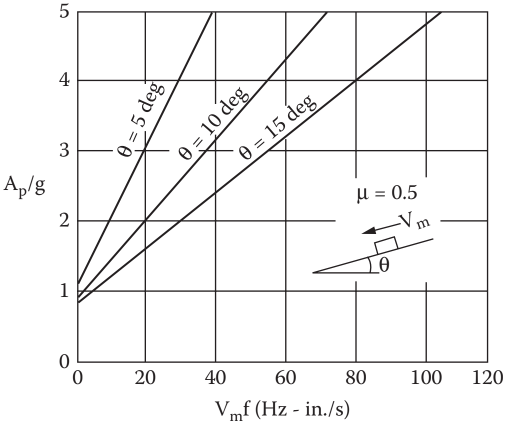


FIGURE 5.22 Effect of parallel track acceleration on mean conveying velocity.

$$v_m = \frac{(\theta/f)(A_p/g + 9.25 \times 10^{-4}\theta^2 - 2.3\mu + 0.25)(25.4)}{0.007\theta + 0.07 + 0.8\mu} \tag{5.42}$$

where v_m is the mean conveying velocity in units of mm/sec, f is the vibration frequency in units of Hz, θ is the inclination of downward-sloping track in degrees, μ is the effective coefficient of friction between part and track, A_p is the parallel track acceleration in units of mm/sec², and g the acceleration due to gravity (9810 mm/sec²).

Equation 5.42 applies when $A_p/g \geqslant 2.0$, $0.3 \leqslant \mu \leqslant 0.8$, $5 \leqslant \theta \leqslant 25$, and when $\theta \leqslant 28.5\mu + 2.5$.

5.2.1 EXAMPLE

A track inclined downward at 10° is vibrated parallel to itself at a frequency of 60 Hz with an amplitude of vibration of 0.2 mm. If the coefficient of friction between the part and the track is 0.5, the mean conveying velocity of the part may be estimated as follows. The dimensionless parallel track acceleration is given by

$$\frac{A_p}{g} = \frac{(0.2)(120\pi)^2}{9810} = 2.9$$

Because $\theta \leqslant 28.5\mu + 2.5$ and $A_p/g > 2.0$, Equation 5.42 applies and, therefore,

$$v_m = \frac{(10/60)[2.9 + 9.25 \times 10^{-4} \times 10^2 - 2.3(0.5) + 0.25](25.4)}{0.007(10) + 0.07 + 0.8(0.5)} = 16 \text{ mm/sec}$$

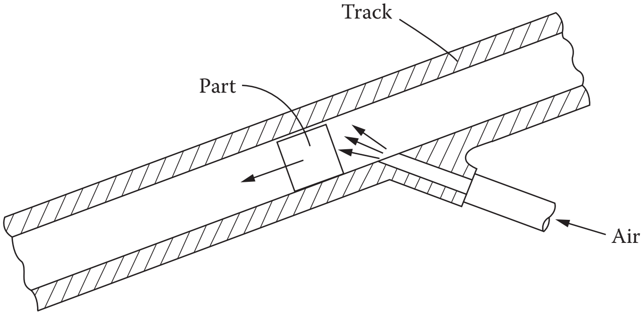


FIGURE 5.23 Air-assisted feed track.

Air-assisted feed tracks are often simply gravity feed tracks with air jets suitably placed to assist the transfer of the parts (Figure 5.23). These devices are ideal for conditions in which the gravity feed track alone will not quite meet the requirements. Although a well-designed air-assisted feed track can, under suitable conditions, feed parts up an inclined track, it is more usual for the track to slope downward or to be horizontal.

For all types of feed tracks, two important points must be considered. For good utilization of space, a feed track should not be too long. Conversely, the feed track, besides acting as a transfer device, provides a buffer stock of parts that, if a blockage occurs, will allow the workhead to continue operating for a limited period. Ideally, the feed track should be capable of holding enough parts to ensure that the workhead can continue to operate long enough to allow the blockage to be detected and cleared.

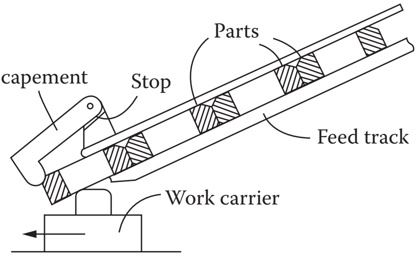
A further requirement for all feed tracks, and indeed all parts feeders and workheads, is that in the event of a blockage, the parts are readily accessible. For this reason, feed tracks should be designed to allow easy access to all parts of the track.

5.3 ESCAPEMENTS

Many types of escapements have been developed and, quite often, for a given part, several available types will perform the required function. Figure 5.24 shows two examples of what is probably the simplest type of escapement. Here the parts are pulled from the feed track by the work carrier, and the escapement itself consists of only a rocker arm or a spring blade.

Many escapements are not always recognized as such. For example, a rotary indexing table may be arranged to act as an escapement. This is shown in Figure 5.25, where parts may be taken from either a horizontal-delivery feed track or a vertical-delivery feed track.

An advantage of the simple escapements illustrated in Figure 5.24 and Figure 5.25 is that they also act as parts-placing mechanisms. The two escapements shown in Figure 5.24 are somewhat unusual in that they are activated by the work



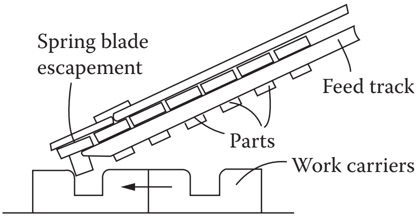
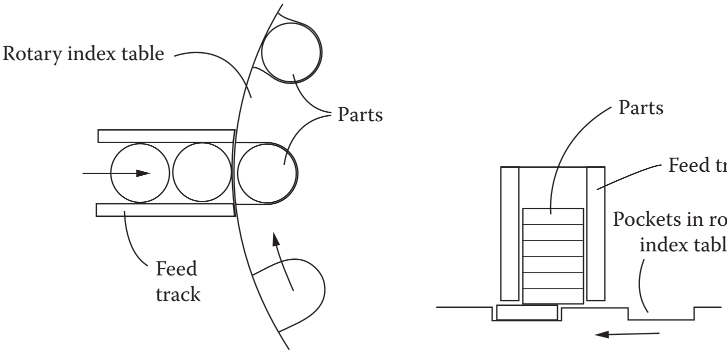


FIGURE 5.24 Escapements actuated by the work carrier.



(a) Horizontal delivery (b) Vertical delivery

FIGURE 5.25 Feeding of parts onto rotary indexing table.

carrier and part, whereas with most escapements, the motion of the part is activated by the escapement which, in turn, is activated by some workhead function. This latter method is the most common in practice, and escapements of this type may be subdivided into various categories, as described in the following subsections.

5.3.1 RATCHET ESCAPEMENTS

Two examples of ratchet escapements are shown in Figure 5.26, the functions being performed are different in each case. The pawl is designed so that as its front finger lifts clear of the line of parts, its back finger retains either the next

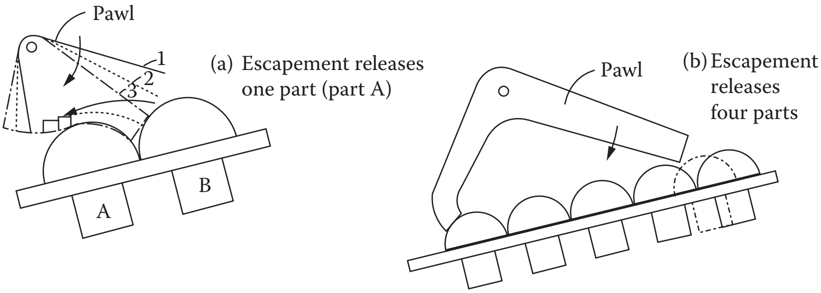

Pawl
1
2
3
(a) Escapement releases one part (part A)
A
B
Pawl
(b) Escapement releases four parts

FIGURE 5.26 Rachet escapements operated by rotary motion.

part as shown in Figure 5.26a or a part further up the line as shown in Figure 5.26b. Ratchet escapements operating on several feed tracks can be activated from a single mechanism. In automatic assembly, the release of several parts from a single feed track is not often required, but the release of one part from each of several feed tracks is often desirable. This can be achieved by a series of ratchet escapements of the type shown in Figure 5.26a. As the escapement is activated, the front finger rotates but without moving the part to be released. At position 2, the front finger is just about to release part *A*, and the back finger moves in such a way that no motion is imparted to part *B*. On the return stroke of the escapement, part *B* is released by the back finger and retained by the front finger.

Figure 5.26b shows a similar type of mechanism except that the remaining parts in that track move forward before being retained by the back finger. In these devices, the back finger of the escapement should not produce motion of the parts opposite to the direction of flow. If this tendency is present, either all the parts above this point on the feed track will move backward and may subject the escapement to heavy loads, or the parts may lock and cause damage to the escapement.

In the examples already shown, the motions of the front and back fingers of the escapement are obtained by a rotary motion. However, the fingers of a ratchet escapement may be operated together or independently by cams, solenoids, or pneumatic cylinders, giving a linear motion as shown in Figure 5.27.

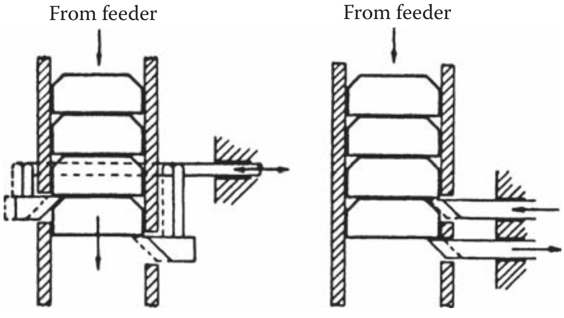


FIGURE 5.27 Ratchet escapements operated by linear motion.

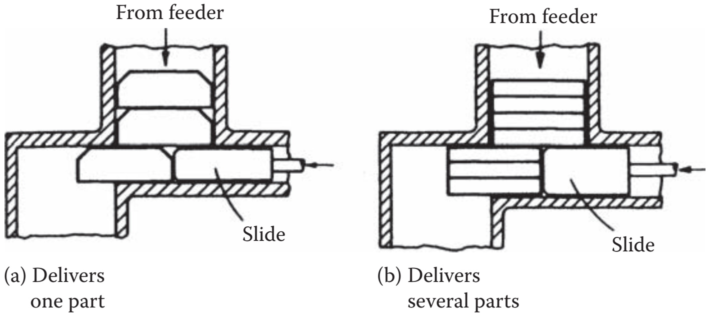


FIGURE 5.28 Slide escapements delivering into single feed chute.

It is clear from all the foregoing examples that the escapement can be used only to regulate the flow of parts that, when arranged in single file, have suitable gaps between their outer edges.

5.3.2 SLIDE ESCAPEMENTS

Five examples of slide escapements are shown in Figure 5.28 to Figure 5.30. It can be seen from the figures that in the slide escapement, one or more parts are removed from the feed chute by the action of a cross slide and that applications of this type of device are restricted to parts that do not interlock with each other. The slide escapement is ideally suited to regulating the flow of spherical, cylindrical, or plate-like parts and although, as shown in Figure 5.28 to Figure 5.30, the feed track enters the escapement vertically, this is desirable but not necessary.

As with the ratchet escapement, parts may be released either singly or in batches from one or a number of feed tracks by the action of a single actuating mechanism. A further alternative, not available with the ratchet escapement, is

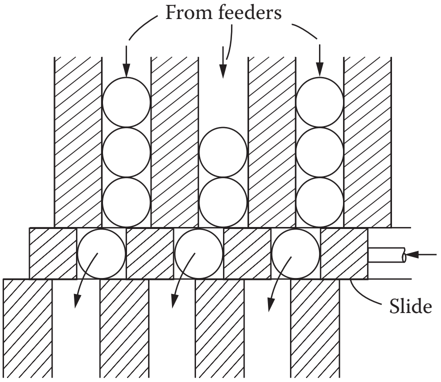
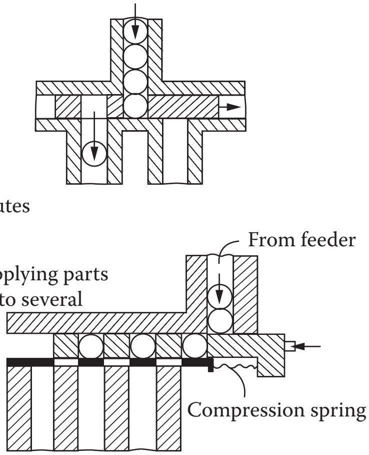


FIGURE 5.29 Slide escapements operating several feed chutes.


(a) Escapement supplying parts alternately to two delivery chutes

(b) Escapement supplying parts simultaneously to several delivery chutes

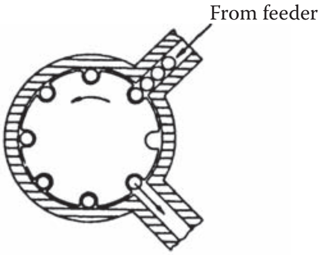
FIGURE 5.30 Slide escapements supplying two or more delivery chutes from a single feed chute.

for parts fed from a single feed track to be equally divided between two delivery tracks, as shown in Figure 5.30a. This type of escapement is very useful where two identical parts are to be used in equal quantities and a parts feeder is available that will deliver at a sufficient rate to meet the total requirement. If it is necessary to feed parts from a single feed track into more than two delivery tracks, a slide escapement of the type shown in Figure 5.30b is suitable. The figure shows three delivery tracks being fed from a single feed track and, as before, only one actuator is necessary.

5.3.3 Drum Escapements

Two types of drum escapements, usually referred to as *drum-spider* escapements, are shown in Figure 5.31 where, in these cases, the drum is mounted vertically and the parts are either fed and delivered side by side (Figure 5.31a) or fed end to end and delivered side by side (Figure 5.31b). In the latter case, the parts are fed horizontally to the escapement. One advantage of the vertical drum escapement is that a change in the direction of motion of the parts is easily accomplished. This can be very useful where the horizontal distance between the parts feeder and the workhead is restricted to a value that would necessitate very sharp curves in the feed track if an alternative type of escapement is used. A further feature of the drum-spider escapement is that the parts on passing through the escapement can be turned through a given angle.

Two other types of drum escapements, the *star wheel* and the *worm*, are shown in Figure 5.32. It can be seen that the direction of motion of the parts is unaffected by the escapement and the parts must have a suitable gap between their outer edges when they are arranged in single file.



(a) With this escapement, parts are fed and delivered side by side

(b) With this escapement, parts are fed end to end and delivered side by side

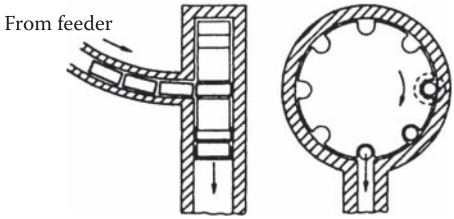
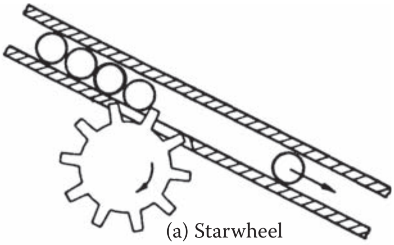
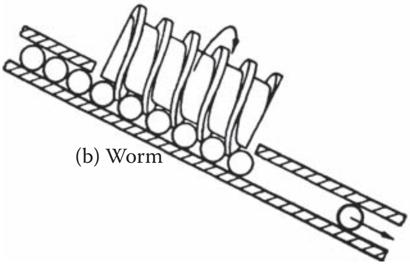


FIGURE 5.31 Drum-spider escapements.



(a) Starwheel



(b) Worm

FIGURE 5.32 Star wheel and worm escapements.

Drum escapements may be driven continuously or indexed, but usually an indexing mechanism is preferable because difficulties may be encountered in attempts to synchronize a continuous drive to meet the requirements of the workhead. Of the four types of drum escapements described (Figure 5.31 and Figure 5.32), the first two are effectively rotary slide escapements and the latter two are rotary ratchet escapements.

5.3.4 GATE ESCAPEMENTS

The gate escapement is seldom used as a means of regulating the flow of parts to an automatic workhead on a mechanized assembly machine. Its main use is to provide an alternative path for parts and, in this capacity, it is often used for removing faulty parts from the main flow. However, one type of gate escapement, shown in Figure 5.33, can be used to advantage on certain types of parts when it is necessary to provide two equal outputs from a single feed track input. It is clear from the figure that although this device is usually referred to as an escapement, it does not regulate the flow of parts, and further escapements would be necessary on the delivery tracks to carry out this function.

5.3.5 JAW ESCAPEMENTS

Jaw escapements are particularly useful in automatic assembly applications in which some forming process is necessary on the part after it has been placed in position in the assembly. Figure 5.34a shows an example of such an application.

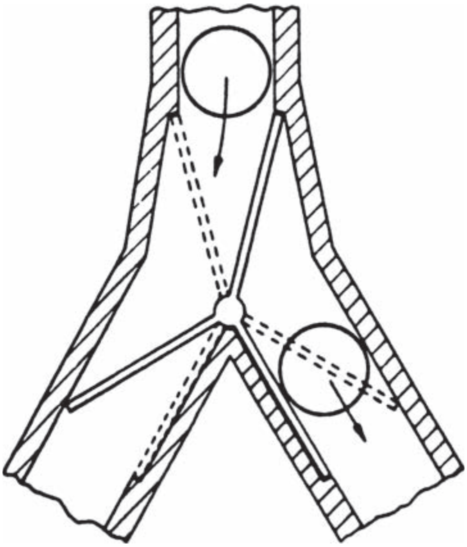


FIGURE 5.33 Gate escapement.

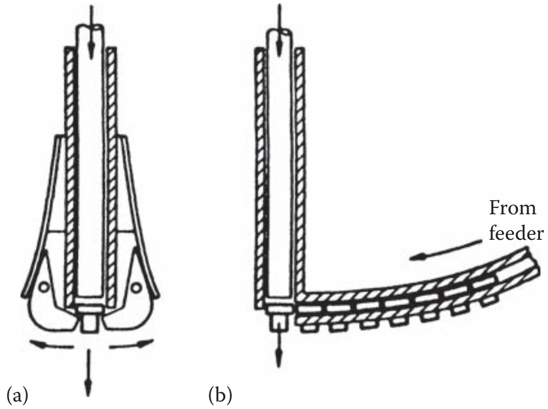


FIGURE 5.34 (a) Jaw escapement and (b) assisted gravity-feed parts-placing mechanism.

The part is held by the jaws until the actuator, in this case a punch, forces that part through the jaws. The punch then performs the punching operation, returns, and allows another part into the jaws. The device can, of course, be used purely as an escapement.

5.4 PARTS-PLACING MECHANISMS

Two simple types of parts-placing mechanisms have already been described and illustrated in Figure 5.24 and Figure 5.25. In the first two examples, the parts are taken from the feed track by the work carrier and, in the other cases, the parts are fed by gravity into pockets on a rotary indexing table. These special applications, however, can be used only for a limited range of parts, and by far the most widely used parts-placing mechanism is a conventional gravity feed track working in conjunction with an escapement. This system of parts placing is probably the cheapest available, but it has certain limitations. First, it may not be possible to place and fasten parts at the same position on the machine because of interference between the feed track and the workhead. This would necessitate a separate workstation for positioning the part, which would result in an increase in the length of the machine. It then becomes necessary to retain the part in its correct orientation in the assembly during transfer. Second, if a close fit is required between the part and the assembly, the force due to gravity may not be sufficient to ensure that the part seats properly. Third, if the part cannot be suitably chamfered, the gravity feed track may not give the precise location required. However, for placing screws and rivets prior to fastening, which forms a large proportion of all parts-placing requirements, and where the tool activates the escapement and applies the required force to make assembly possible, the gravity feed track is invariably used. An example of automatic screw placing and driving is shown in Figure 5.35.

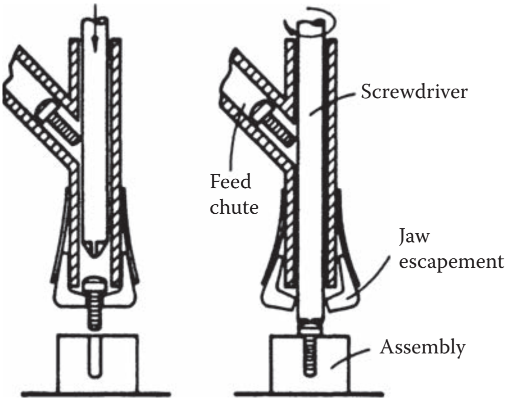


FIGURE 5.35 Parts-placing mechanism for automatic screwdriver.

A further example of the assisted gravity-feed type is shown in Figure 5.34b, where a part is being positioned in the assembly. With this device, the feed track positions the part vertically above the assembly. The part is then guided into position in the assembly by a reciprocating guide rod. With these systems, it is common to fit the escapement at the point at which the guide rod operates and to use the guide rod as the escapement activator. In some applications, the part may be positioned above the assembly by means of a slide escapement and then guided into position using a guide rod. This system is commonly referred to as the *push-and-guide system* of parts placing.

For situations in which the placing mechanism has to be displaced from the workstation location, the *pick-and-place system* is often used. The basic action of this system is shown in Figure 5.36 and Figure 5.37, where it can be seen that the part is picked up from the feed track by means of a mechanical, magnetic, or vacuum hand depending on the particular application, placed in position in the assembly, and then released. The transfer arm then returns along the same path to its initial position. Some units pick vertically, transfer along a straight path horizontally, and place vertically, as shown in Figure 5.36a. Others pick vertically, transfer around the arc of a circle in a horizontal plane, and place vertically, as shown in Figure 5.36b. A third type picks and places by rotary motion of the transfer arm in a vertical plane and, throughout transfer, the hand remains vertical (Figure 5.37a). Finally, a variation of this latter type has the pickup head fixed to the arm, and the part is turned over during the operation (Figure 5.37b). When operating correctly, the first two examples can mate parts that have close assembly tolerances and no chamfers, whereas the latter two examples, although the simplest systems, can operate only when the length of the vertical contact between the mating parts is small.

On high-speed operations, the pick-and-place mechanisms are usually mechanically actuated and are mechanically connected to the entire assembly operation. Each unit is designed and built for a particular application. However, because of the similarity between many of the assembly operations, modular

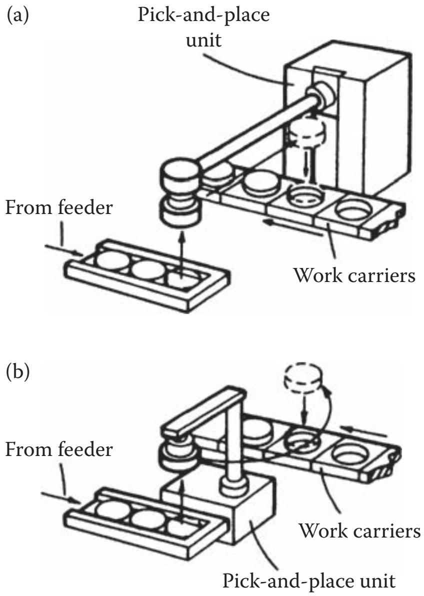


FIGURE 5.36 Pick-and-place units that lift and position vertically.

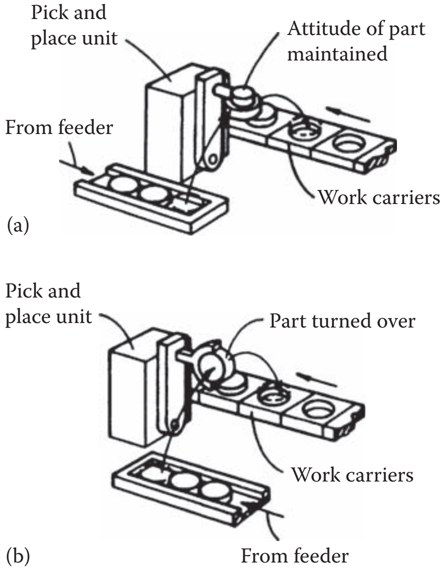


FIGURE 5.37 Pick-and-place units that move the part along the arc of a circle.

pick-and-place mechanisms have been developed. These basically off-the-shelf units can handle a large percentage of assembly operations with little modification. These units, which were developed in-house by assembly machine manufacturers as part of their basic assembly machinery, have been made available by smaller manufacturers as separate items. The modular concept has been successful because many assembly operations consist of the same sequence of simple motions.

Recent studies have indicated that most subassemblies and some complete assemblies can be put together with a single pick-and-place unit with three or four degrees of freedom, as represented by a rectangular or cylindrical coordinate system, with a twisting motion about the major axis. Such a mechanism needs an elaborate control system to handle the larger variety of sequential motions. These systems, including the mechanisms and controls, are called *robots* and can replace the dedicated pick-and-place mechanisms.

5.5 ASSEMBLY ROBOTS

Since the 1970s, great interest has been shown in the use of robots in assembly automation. High-speed automatic assembly is generally applicable only to high-volume production (at least one or two million per year) and in situations in which the product design is stable and a steady demand is anticipated. In the early 1970s, it was felt that the introduction of general-purpose assembly robots would allow the application of automation to the assembly of products that did not meet these high-volume production requirements. The dream was to develop assembly systems so flexible that they could be quickly adapted and reprogrammed to assemble different products in medium, or even small, batches. Companies purchased assembly robots in order to test them on their own products, but the results were disappointing. Unfortunately, in the U.S., interest concentrated on the high-technology aspect of robotics, including vision systems, tactile sensing, and expensive multi-degree-of-freedom robots expected to operate at a single workstation and perform the tasks of a human assembly worker. Indeed, one of the more popular U.S. assembly robots, the PUMA, was designed to have reach and dexterity characteristics similar to those of a human being.

In the meantime, in Japan, a more practical approach was being used in which robots were treated simply as another tool to be applied, where suitable, to assist in assembly work.

Before examining this situation in greater detail, let us clarify some of the terminology being used and then look at some of the advantages of assembly robots.

5.5.1 TERMINOLOGY

Assembly automation equipment used in mass production is often referred to as *dedicated* equipment. Assembly automation of the more flexible kind is referred to as *programmable* or *adaptable assembly* or just *robot assembly.* Unfortunately, the use of these terms sometimes leads to considerable confusion. For example, a multistation assembly machine for producing one tape-deck mechanism every few seconds would be regarded as a dedicated machine. However, this machine could be directed by a computer to skip assembly stations on command and thereby produce various styles of the tape deck. We would now have a programmable machine, and yet no assembly robots would be involved. On the other hand, an assembly system could be developed that uses one or more assembly robots to assemble the tape decks. The machine could still be dedicated to the one product, but we now have programmable or robot assembly.

In fact, almost all robot assembly applications in present practice use the robots as dedicated equipment, and the basic programming of the robot might be done only during initial setup of the system, with occasional reprogramming to allow for design changes or style variations. Hence, it is misleading and confusing to speak of robot assembly equipment or programmable assembly equipment as the alternative to dedicated assembly equipment.

In this book, the term *special-purpose* is used to describe equipment or tooling that is custom-made for one product or part, and the term *general-purpose* is used to describe equipment or tooling that can be readily adapted or programmed for a variety of products or parts.

5.5.2 ADVANTAGES OF ROBOT ASSEMBLY

Some of the main advantages in the use of assembly robots can be described with reference to the conditions for the economic application of special-purpose assembly machines:

1. *Stability of the product design:* If the product design changes, the robot can be reprogrammed accordingly. However, this does not usually apply to the peripheral items in the system that contact the parts, such as feeders, grippers, etc.
2. *Production volume:* As will be seen, a robot system can operate economically at much longer station cycle times than a high-speed automatic assembly machine. (The station cycle time is the interval between the production of completed assemblies.)
3. *Style variations:* A robot system can be more readily arranged to accommodate various styles of the same product. For example, the robot can be reprogrammed to select only certain parts for the assembly, depending on the particular style required.
4. *Part defects:* First, it is interesting to note that a feeder jam caused by a faulty part causes much greater loss in production on a high-speed transfer assembly machine than on a robot system with a relatively long cycle time. In addition, the robot can be programmed to sense problems that may occur and to reattempt the insertion procedure.
5. *Part size:* As will be seen later, a principal advantage of a robot used in assembly is that the parts can be presented in patterns or arrays on pallets or part trays. In this case, the severe restrictions on part size in high-speed automation do not apply.

In the automatic assembly of one part, there are two principal steps: (1) the handling and presentation of the part to the insertion device and (2) the insertion of the part. Depending on the circumstances, either or both of these steps might be carried out automatically, and the last step (insertion) might be carried out by an assembly robot. It is useful to consider the alternatives for the automation of the insertion operation, assuming that the parts can be presented at the required frequency and in the same orientation. First, robot arms can be employed. However, it should be noted that there are some insertion processes a robot usually cannot perform without the aid of special workstations. These include, for example, all insertion or fastening operations requiring the application of large forces. Also, there are some processes that a robot cannot perform without using special tools. These include screw insertion, spot welding, etc. For many of these cases, a single-part special-purpose workhead can be used that is a mechanism or machine designed to perform the insertion operation repeatedly.

On the other hand, there are some operations that require such complicated manipulations that a robot under program control is essential. These include following a contoured seam in welding operations or running a wire through a complicated path. However, the more fundamental difference between a robot and a single-part, special-purpose workhead is that the workhead can perform only the one operation repeatedly, whereas the robot can perform a sequence of different operations repeatedly.

When the required assembly rate is high, a transfer machine is required and, at each station, the same operations must be performed repeatedly. Under these circumstances, the decision to use a special-purpose workhead or a robot at a particular station depends on the nature of the insertion operation and on the cost of the equipment. By the time a special-purpose workhead has been adapted and engineered for an assembly machine and then debugged, its final cost may be double the original cost. One advantage of a robot is the reduction in the cost of adaptation.

It would appear that, from the viewpoint of the economics of the assembly processes, the main distinguishing features of a robot are that it can be programmed to perform a cycle of several different operations quickly and can be engineered easily to adapt to changes in product design or style variations.

In this book, it has been seen that automatic parts presentation is one of the major problems in high-speed automatic assembly. Parts must be presented to a single-part, special-purpose workhead in the same orientation at the same location. Vibratory-bowl feeders and a variety of mechanical feeders can be economically used for this purpose as long as the part is small and is required at relatively frequent intervals. These conditions arise from the fact that the cost of automatically feeding a part is proportional to the length of the assembly cycle.

For example, if it is assumed that simple parts 25 mm long can be fed using a vibratory-bowl feeder, at 1/sec at a cost of 0.04 cents each, and then with the same bowl feeder, a part 250 mm long would take 10 sec to deliver at a cost of 0.4 cents. Because it would cost about 0.4 cents for an assembly worker to perform the operation, it would not be economical to feed larger parts automatically.

Correspondingly, it would not be economical to employ a vibratory feeder if the assembly cycle is relatively long. It is assumed here that the part does not present particular feeding and orienting problems because of geometry, flexibility, or fragility, etc. If any of these problems exist, then the economics of automatic handling would be even less attractive.

Another method of parts presentation is by magazine. Sometimes the parts can be purchased in connected form like staples or secured to paper strips and coiled, as with many electronic components. Under these circumstances, the orientation is carried out by the manufacturer, and this makes parts presentation in automatic assembly relatively inexpensive.

Under some conditions, it is economical to have a special magazine associated with the special-purpose workhead and load this with parts manually. In this case, the part orientation is done manually, either at the machine or "off-line." If the loading is done off-line, there is the possibility that the magazines can be loaded automatically, sometimes immediately after part manufacture. This situation lends itself to preinspection to avoid assembly machine downtime due to faulty parts.

When assembly robots are employed, further important possibilities exist for parts presentation:

1. Some parts may be presented partially oriented, and the robot can perform final orientation.
2. Identical parts may be presented in pallets or part trays in fixed arrays.
3. Sets of different parts can be presented in part trays (kits).
4. Feeders might be used that can feed different parts simultaneously.

We can conclude that an added advantage of the use of assembly robots is the widely increased alternatives allowed in the methods of parts presentation. Some of these alternatives will now be discussed in greater detail.

5.5.3 MAGAZINES

Part magazines provide one of the more convenient ways to present parts to the assembly system and have been studied by Arnstrom and Grondahl [4]. The purposes of a magazine are twofold: (1) to present the parts in the same orientation to the robot and (2) to decouple the manual handling process from the machine cycle time.

If both these requirements are met, the assembly system is able to operate automatically. Often, the requirements can be met with simple and inexpensive methods. Sometimes, however, questions concerning space requirements, precision, transportation, storage, and cost must be carefully considered. Magazines can perform the following additional functions:

1. If part manufacture and assembly can be integrated, the magazine can form a buffer between the two operations. This can help to balance fluctuations in the cycle time and minimize imbalances between manufacturing and assembly requirements.

2. The magazine can provide a method for holding the parts during transportation and, hence, rationalize transportation procedures as well as minimize the risk of damage to the parts.
3. Magazines can help to simplify the problems of part storage and inventory control.

It is important to make a distinction between a magazine and a buffer. The objective in using a magazine is primarily to decouple the operator from the machine to avoid costly idle time when the operator has to wait for the machine or the machine has to wait for the operator.

The magazine coupled directly to the assembly system creates opportunities for the operator to attend to other aspects of machine loading. The function of a buffer is to decouple one machine station from the adjacent station. The buffer accommodates the idle times that would occur if one station had to wait for another. A buffer eliminates varying imbalances between stations on a free-transfer, multistation machine.

5.5.4 Types of Magazine Systems

Figure 5.38 presents a rough classification of different magazine configurations. This classification is based on the requirements imposed by the part-presentation mode on the robot motions. It should be noted that the part-presentation mode also influences the space requirements for the magazine. Magazines can be divided into two basic types:

1. Part presentation at a single location (Figure 5.38a). With these magazines, the robot acquires the part always at the same location. The parts move within the magazine and are fed by gravity or a driving force, such as that exerted by a spring each time a part is removed from the magazine.
2. Part presentation at multiple locations (Figure 5.38b). In these magazines, the parts are placed in a fixed array. The robot must be programmed to acquire the parts in a predetermined pattern (pattern picking).

5.5.5 Automatic Feeders for Robot Assembly

Numerous developments in automatic parts feeding for robot assembly are taking place. These range from simple mechanically adjustable feeders to sophisticated "vision" systems. Because it is not possible to review in this book all the different approaches, only a few representative examples will be mentioned. Examples will be limited to those that seem to hold both practical and economic possibilities.

One important objective in any feeder suitable for robot assembly is to minimize the ratio of the total cost of the feeder to the number of different parts to be fed. Several so-called multipart feeders have been under development, some

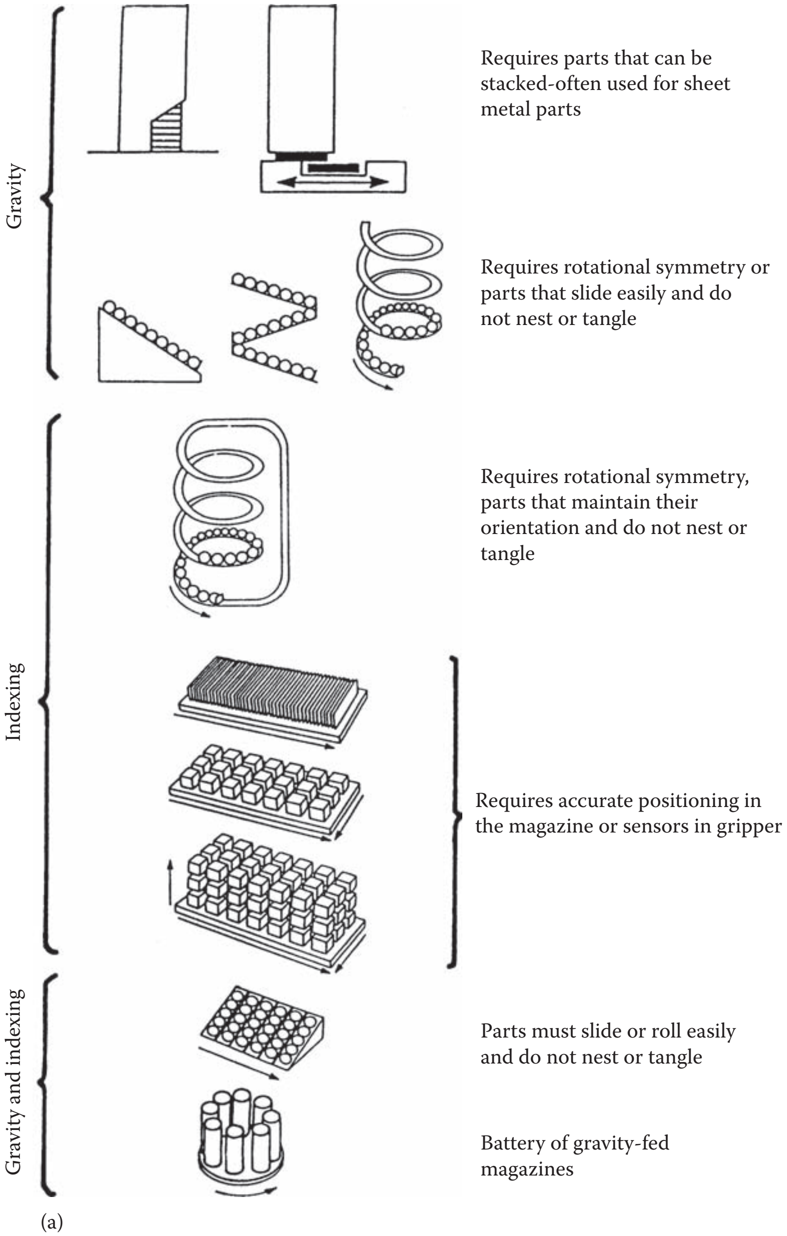
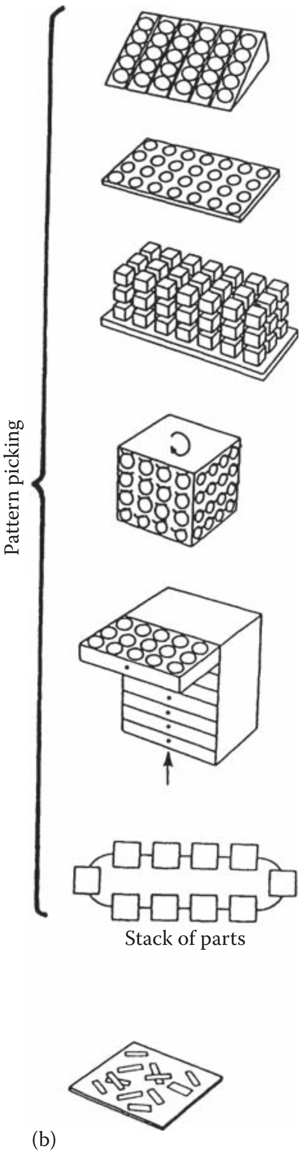

Gravity
Requires parts that can be stacked-often used for sheet metal parts
Requires rotational symmetry or parts that slide easily and do not nest or tangle
Indexing
Requires rotational symmetry, parts that maintain their orientation and do not nest or tangle
Requires accurate positioning in the magazine or sensors in gripper
Gravity and indexing
Parts must slide or roll easily and do not nest or tangle
Battery of gravity-fed magazines
(a)

FIGURE 5.38 Part magazine configurations: part presentation (a) at a single location and (b) at multiple locations. (From Arnstrom, A. and Grondahl, P., Magazines for Flexible Automatic Assembly, IVF - Result 83607, Stockholm, 1983.)



In y direction	Requires parts with rotational symmetry or parts that slide easily
In x and y directions	Requires accurate positioning in magazine or sensors in gripper
In x, y and z directions	As above but it must also be possible to stack parts
In y and z directions with rotation of magazine	For parts that can hang
In x and y directions with indexing in z direction	For parts that must be protected
In z direction with indexed conveyor	For parts that can be stacked
Randomly oriented and positioned parts-requires sophisticated robot with vision (bin picking)	

FIGURE 5.38 (Continued)

employing vision systems such as the Hitachi feeder [5], and at least one in which interchangeable mechanical tooling is used, such as the so-called Salford feeder [6].

In the Hitachi feeder, several vibratory bowls (one for each different part) feed the parts without orientation to a vision station. Each part is held momentarily in the station, where a camera determines which of the limited number of possible stable orientations exist. This information then allows the robot to grip the part correctly and perform the necessary orientation when transferring it from the feeder to the assembly. Such an arrangement allows the relatively large cost of the equipment to be distributed among several parts. In addition, the amount of special-purpose equipment is kept to a minimum.

The technique of employing a simple vision system to distinguish between a limited number of part orientations in this way was first developed by Heginbotham et al. [7] and was later applied to a multipart feeder [5].

The Salford multipart feeder [6] consists of a linear vibratory drive onto which several different straight feed tracks can be mounted, with provision for returning rejected parts to the beginning of each track using a reciprocating elevator. The feed tracks are machined especially for each part. The cost of each track is kept to a minimum by using a library of programs for an N.C. milling machine. The orienting devices that can be machined in this way are limited in type so that the feeder is not as versatile as a vibratory-bowl feeder. Nevertheless, the total cost of the feeder per part type is likely to be very low, making it a most attractive proposition in suitable circumstances. One disadvantage with multipart feeders is that they will not necessarily be applicable in multistation robot systems. Such a feeder can be used only when a significant number of parts being assembled at a particular station can be fed by that feeder.

Single-part feeders for robot assembly (Figure 5.39) have been developed [8]. These are based on the double-belt principle and, for many simple rotational parts, require only one interchangeable blade to perform all the necessary orientations. For rotational parts with asymmetric grooves or holes, the final orientation can be performed by the robot, which is programmed to rotate the part above a single sensor until the feature is detected. This operation leads to an increase (of about 1 or 2 sec) in the station cycle time.

For nonrotational parts, the same feeder can be fitted with a single sensor and a solenoid-activated rejection device. Such an arrangement is capable of handling a very wide range of parts.

One particularly useful attribute of these double-belt feeders is that no special-purpose delivery track is required, and special-purpose tooling costs can be kept to a minimum.

5.5.6 ECONOMICS OF PART PRESENTATION

A study [9] has been made of the comparative economics of a range of part-presentation devices. The study was based on the idea that the cost per part type of any part-presentation system can be divided into three components:

1. The basic cost of the feeder (general-purpose equipment)
2. The cost of the tooling that is special to the part under consideration (special-purpose equipment)
3. The cost of manual labor

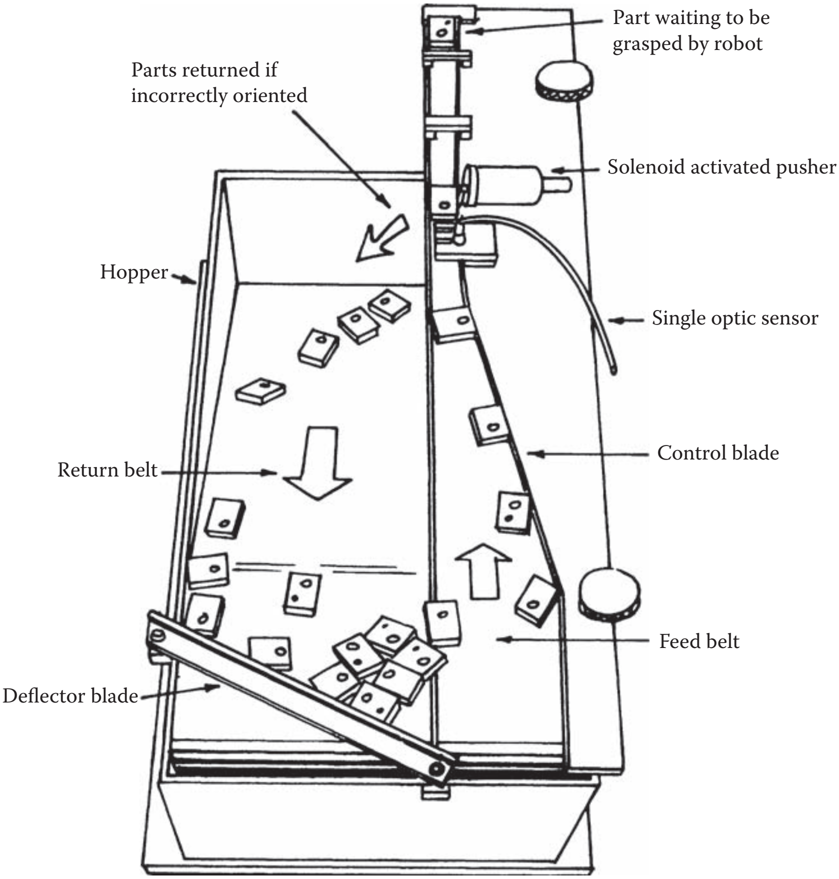

Part waiting to be grasped by robot
Parts returned if incorrectly oriented
Solenoid activated pusher
Hopper
Single optic sensor
Control blade
Return belt
Feed belt
Deflector blade

FIGURE 5.39 Double-belt feeder. (From Zenger, D. and Dewhurst, P., Automatic Handling of Parts for Robot Assembly, *Annals of the CIRP*, Vol. 33, No. 1, 1984, p. 279.)

In multistation machines, it is possible to interpose manual assembly stations between automatic stations, whereas in single-station robot systems, it is not usually feasible for safety considerations to arrange for manual operations within the system cycle. For those situations in which manual insertion of parts is a possible alternative, the cost C_{mi} for the manual insertion of one part would be given by

$$C_{mi} = (t_{at}/n_a)W_a \text{ cents} \tag{5.43}$$

where t_{at} is the machine cycle time (sec), n_a the number of parts manually assembled consecutively during one machine cycle, and W_a the assembly worker rate (cents/sec).

Normally, n_a will be unity and, because a typical average manual assembly time is 8.25 sec [10], Equation 5.43 is valid only for values of t_{at} greater than this. However, in some multistation free-transfer machines using robots, the station cycle time may be long enough to allow two or three operations at one manual station. In these cases, n_a in Equation 5.43 would be increased and the minimum value of t_{at} would increase proportionally. Rather than present the costs of manual insertion as a step function, we will assume that these are given by

$$C_{\text{mi}} = 8.25\ W_a \text{ cents} \tag{5.44}$$

Equipment is needed for all other part-presentation methods, and the calculations of presentation costs depend on the size of the product batch. When the batch is small, the cost attributable to special-purpose tooling is given by distributing the equipment cost over the batch. The cost attributable to equipment that can be reused is obtained by depreciating the equipment cost over the time worked during the equipment payback period. Thus, in general, for small batches, the cost of automatic part presentation is given by

$$C_f = C_{\text{gp}}(0.014/P_s)t_{\text{at}} + 100C_{\text{sp}}/B_s \text{ cents} \tag{5.45}$$

$$\begin{array}{ccccc} \text{Cost of} & & \text{Cost of using general-} & & \text{Cost of using} \\ \text{part} & = & \text{purpose equipment} & + & \text{special-purpose} \\ \text{feeding} & & & & \text{equipment} \end{array}$$

where C_{gp} and C_{sp} are general-purpose and special-purpose equipment costs, respectively (in thousands of dollars), P_s is the number of shift-years in the payback period, and B_s is the size of the batch (in thousands) to be produced during the equipment payback period. It should be noted that the constant 0.014 is a combined factor to convert shift-years to seconds and dollars to cents. If the time taken to manufacture the complete batch ($t_{\text{at}}B_s$) is greater than the equipment payback period P_s, then Equation 5.45 becomes

$$C_f = (C_{\text{gp}} + C_{\text{sp}})(0.014/P_s)t_{\text{at}} \text{ cents} \tag{5.46}$$

For manually loaded magazines, the general-purpose portion of the equipment cost will be small, but an extra term must be added to allow for the cost of manual handling for loading each part into the magazine. This cost is given by multiplying the manual assembly time t_m by the assembly worker rate W_a and is estimated to be approximately 0.7 cents [10]. Thus, the cost of part presentation by manually loaded magazine C_{mm} becomes

$$C_{\text{mm}} = 100C_{\text{sp}}/B_s + t_mW_a \text{ cents}$$

when $t_{\text{at}}B_s < 7200\ P_s$ and

$$C_{\mathrm{mm}} = C_{\mathrm{sp}}(0.014/P_s)t_{\mathrm{at}} + t_m W_a \text{ cents} \tag{5.47}$$

when $t_{\mathrm{at}}B_s > 7200\ P_s$.

Equation 5.44 to Equation 5.47 can be used to determine, for any part-presentation method, the conditions for which the method would be economic compared with manual insertion or manually loaded magazines. Figure 5.40 shows the results obtained in this way for the representative part-presentation systems given in Table 5.4. Superimposed on the figure are lines showing values of the total batch-production time, a time given by $t_{\mathrm{at}}B_s$.

It can be seen that when the total batch-production time becomes greater than the equipment payback period, the choice of feeding system becomes independent of batch size. Further, Equation 5.46 shows that it is now the total feeder cost that is important. Under these circumstances, the most attractive presentation methods compared with manually loaded magazines would be the Salford, double-belt, vibratory-bowl, and Hitachi feeders, in that order.

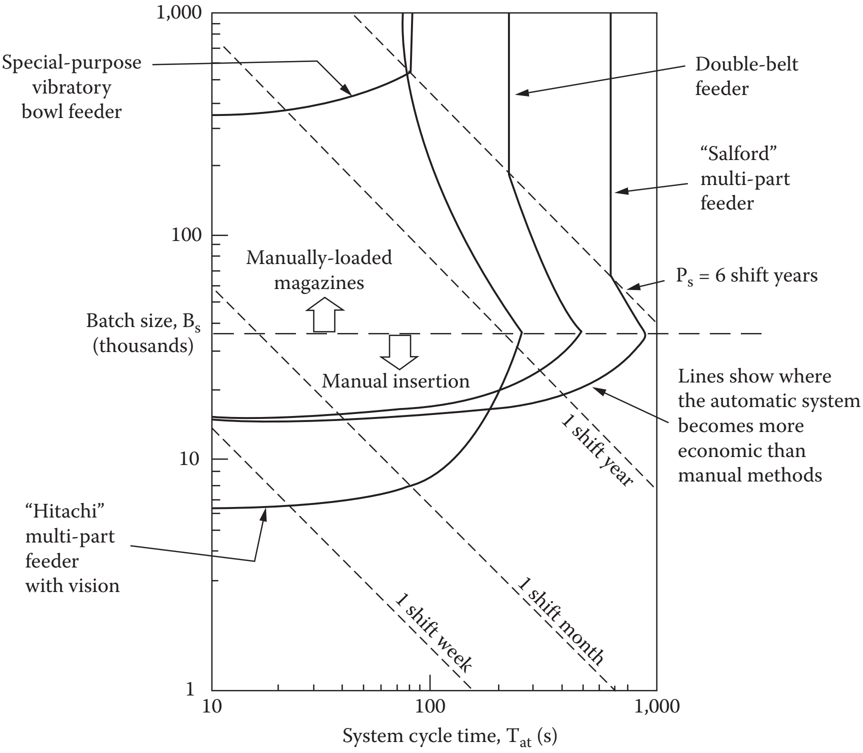


FIGURE 5.40 Economics of some representative part-presentation methods. (From Lennartz, C. and Boothroyd, G., Economics of Part Presentation for Robot Assembly, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, 1984.)

TABLE 5.4
Costs per Part Type for Some Typical Part-Presentation Systems

Name of System	General-Purpose Tooling (C_{gp}) (in Thousands of Dollars)	Special-Purpose Tooling (C_{sp}) (in Thousands of Dollars)	Labor Cost per Part
Vibratory-bowl feeder	1.5	3.5	—
Hitachi multipart feeder	5.0	0.2	—
Salford multipart feeder	1.0	0.5	—
Double-belt feeder	2.0	0.5	—
Manually loaded magazine or pallet	—	1.0	$t_m W_a$[a]

Note: Costs estimated by author.

[a] t_m = time taken to manually load 1 part into magazine or pallet; W_a = operator rate (cents/sec).

When the batch size is reduced, the vibratory-bowl feeder rapidly becomes uneconomical. For batch sizes less than 35,000, the manually loaded magazines are no longer attractive, and manual insertion is preferable. However, the three programmable feeder types are still competitive, the Hitachi feeder being the best alternative for batch sizes as low as 6,500.

The results in Figure 5.40 must be interpreted with care because all the alternatives will rarely be suitable for a particular part.

5.5.7 DESIGN OF ROBOT ASSEMBLY SYSTEMS

The basic configurations of general-purpose assembly robots now being marketed are illustrated in Figure 5.41. Most of these robots are fixed to a base or pedestal, but a significant number employ robot arms suspended from a gantry or portal framework. It should be pointed out that some automatic assembly systems employ one or more insertion devices fixed above an x–y table such as the Sony FX1 system [11] shown in Figure 5.42 or systems for assembling PCBs. Although these systems play an important role in automatic assembly, they will not be considered in the present discussion because they do not involve the application of general-purpose assembly robots.

Assembly robots of the pedestal type can be applied either singly or grouped around one or more stationary work fixtures. They can also be arranged along transfer machines, where each robot will perform several assembly tasks. In either case, the robots can reach into a feeder or pallet to grasp parts.

An example of the single-station robot assembly system has been described by Warnecke and Walther [12]. In this system (Figure 5.43), two robots work at one station to perform some final assembly tasks on automobile engines. One robot performs the parts-handling functions while the other performs the screwing operations. In this way, undesirable gripper or tool changing is avoided. The

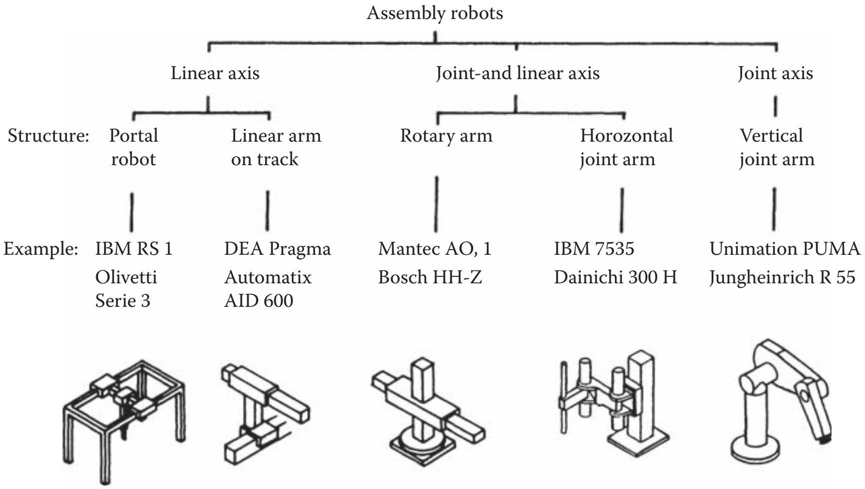


FIGURE 5.41 Configurations of general-purpose assembly robots (courtesy Prof. Warnecke, University of Stuttgart).

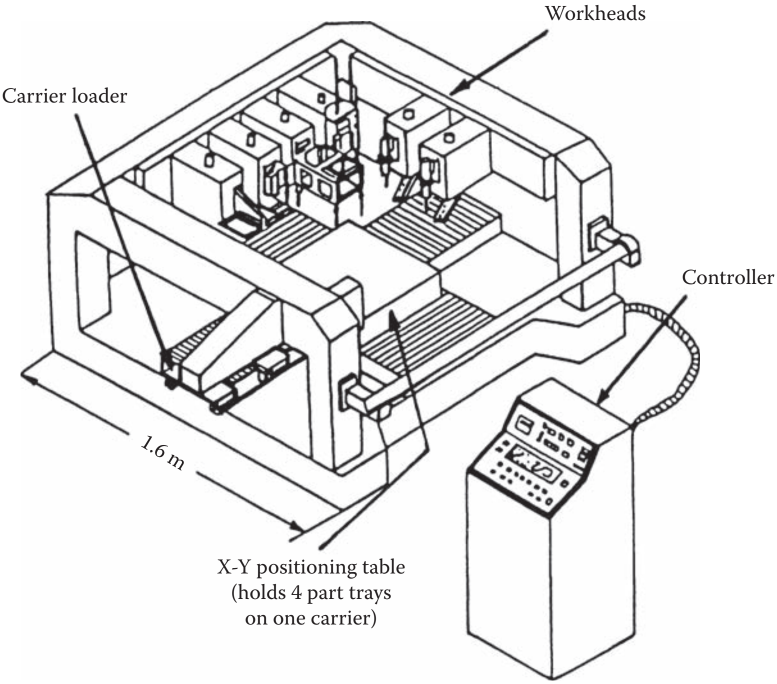


FIGURE 5.42 Sony FX-1 flexible assembly system. (From Taniguchi, N., Present State of the Arts of System Design on Automated Assembly in Japan, *Proceedings of the 4th International Conference on Assembly Automation*, Tokyo, October 1983, p. 1. With permission.)

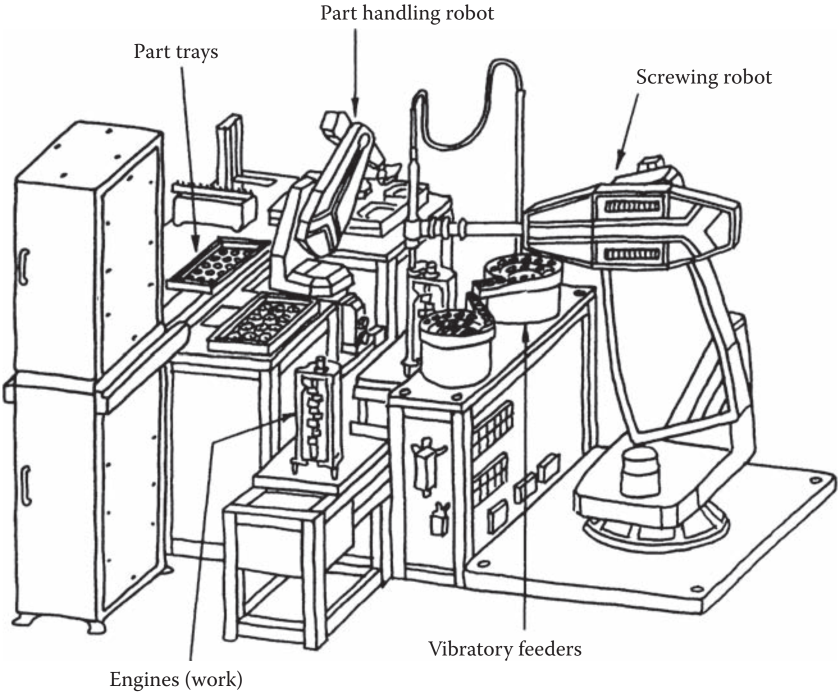
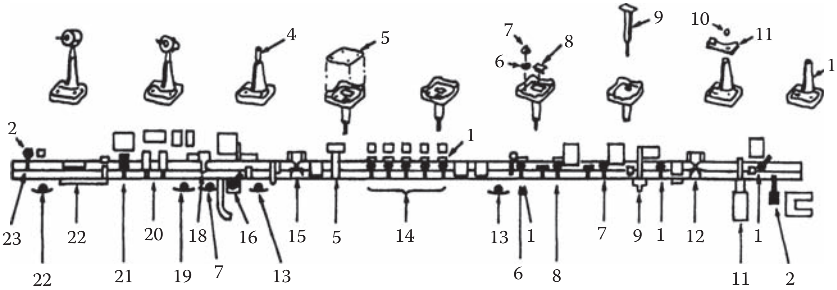


FIGURE 5.43 Single-station two-arm assembly system. (From Warnecke, H.J. and Walther, J., Assembly of Car Engines by Hand in Hand Working Robots, *Proceedings of the 4th International Conference on Assembly Automation*, Tokyo, October 1983, p. 15. With permission.)

assembly tasks involve the addition of four subassemblies or parts and fastening with ten screws. Thus, including the engine assembly itself, 15 subassemblies or parts are handled at the station. The station cycle time is 90 sec (6 sec/part) and the manual assembly time for the same tasks is 3.4 min (13.6 sec/part), giving a payback period of 2.5–3 years.

Taniguchi [11] provides an example of the multistation robot assembly system. This system, developed by the Toshiba Corporation, assembles 24 different styles of electric fans and is based on a free-transfer machine with 24 stations (Figure 5.44). It has 11 general-purpose robots, 2 special-purpose robots, 2 pick-and-place mechanisms, 2 mechanisms for turning over the assembly, 3 special-purpose workheads, and 5 assembly workers.

Both of these systems employ pedestal-type robots. Gantry-type robots are slightly more limited in their applications because they are less convenient to apply in transfer-line situations in which the series of work carriers must pass under the gantry. However, many system developers consider this arrangement quite feasible, and they envision trays of parts being passed from robot to robot by means of a conveyor. Because of the limited space available within the



1 Robotic hand (TSR 700H)
2 Specially designed robotic hand
3 Operator or worker
4 Supporter of neck
5 Bottom plate
6 Condensor
7 Timer
8 Push button switch
9 Slide unit
10 Cap
11 Decorative plate
12 Base of electric fan
13 Assembling of wire code
14 Automatic soldering
15 Turning over of base
16 Fitting of knob of timer
17 Fitting of motor unit
18 Screwing
19 Fitting of motor code
20 YAG Laser soldering of terminal plate
21 Pick and place unit
22 Test unit
23 Ejection unit

FIGURE 5.44 Multistation free-transfer machine employing assembly robots. (From Taniguchi, N., Present State of the Arts of System Design on Automated Assembly in Japan, *Proceedings of the 4th International Conference on Assembly Automation*, Tokyo, October 1983, p. 1. With permission.)

framework of a gantry-type robot, the parts must usually be conveyed into the working space by delivery tracks. Feeders are now being developed that present the oriented parts within the feeder, thus avoiding the need for special-purpose delivery tracks. Because the gantry robot cannot reach outside its framework, such feeders would have to be contained within the framework, which would result in severe space problems.

From the preceding discussion, it can be reasonably assumed for the present purpose that the application of gantry-type robots in assembly is generally limited to those situations in which one or more assemblies are simultaneously built up on stationary work fixtures. Further, most of the parts must be presented either on pallets or part trays, or in feed tracks or magazines loaded manually or automatically off-line.

The purpose of this discussion, however, is not to attempt to determine which is the “best” assembly robot. In the future, important applications will almost certainly be found for all the various types being developed. It would be useful, however, to determine the production circumstances under which various products would lend themselves to the different configurations of complete assembly systems.

Experience shows that there are important fundamental differences between those assembly systems based on a work-carrier transfer system and those non-transfer systems in which the assembly space is restricted. First, most assemblies include parts that must be manually inserted. In the nontransfer systems, manual operations cannot effectively be carried out within the assembly cycle; manual operations can be done only before or after the robot performs the consecutive series of automatic operations. This restriction does not apply to the transfer system because assembly workers can be included at any station along the line. For a particular product, this can have an important influence on both the feasibility of robot assembly and the design of the product.

Second, with the nontransfer systems, there is a direct relation between the cycle time and the number of parts to be assembled during one cycle; the larger the number of parts, the longer the cycle. However, because the number of operations at each station on a transfer system can be varied at the system design stage, this limitation does not exist. If necessary, for assemblies with large numbers of parts, transfer systems with large numbers of stations can be used to keep the cycle time low; this results in greater utilization of feeders.

REFERENCES

1. Boothroyd, G., Poli, C., and Murch, L. E., *Automatic Assembly*, Marcel Dekker, New York, 1982.
2. Murch, L.E. and Boothroyd, G., On-Off Control of Parts Feeding, *Automation*, Vol. 18, August 1970, pp. 32–34.
3. Redford, A.H. and Boothroyd, G., Designing Gravity Feed Tracks for Headed Parts, *Automation*, Vol. 17, May 1970, pp. 96–101.
4. Arnstrom, A. and Grondahl, P., Magazines for Flexible Automatic Assembly, IVF-Result 83607, Stockholm, 1983.
5. Suzuki, T. and Kohno, M., The Flexible Parts Feeder Which Helps a Robot Assemble Automatically, *Assembly Automation*, Vol. 1, No. 2, 1981.
6. Redford, A.H., Lo, E.K., and Killeen, P., Cost Analysis for Multi-Arm Robotic Assembly, *Assembly Automation*, Vol. 3, No. 4, 1983, p. 202.
7. Heginbotham, W.B., Barnes, D.F., Purdue, D.R., and Law, D.J., *Flexible Assembly Module with Vision Controlled and Placement Device*, Production Engineering Research Association, Melton Mowbary, Leicestershire, England.
8. Zenger, D. and Dewhurst, P., Automatic Handling of Parts for Robot Assembly, *Annals of the CIRP*, Vol. 33, No. 1, 1984, p. 279.
9. Lennartz, C. and Boothroyd, G., Economics of Part Presentation for Robot Assembly, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, 1984.
10. Boothroyd, G., Economics of General-Purpose Assembly Robots, *Annals of the CIRP*, Vol. 33, No. 1, 1984, p. 287.
11. Taniguchi, N., Present State of the Arts of System Design on Automated Assembly in Japan, *Proceedings of the 4th International Conference on Assembly Automation*, Tokyo, October 1983, p. 1.
12. Warnecke, H.J. and Walther, J., Assembly of Car Engines by Hand in Hand Working Robots, *Proceedings of the 4th International Conference on Assembly Automation*, Tokyo, October 1983, p. 15.

6 Performance and Economics of Assembly Systems

Multistation assembly machines may be classified into two main groups according to the system used to transfer assemblies from workstation to workstation. The first group includes those assembly machines that transfer all the work carriers simultaneously. These are known as *indexing* or *synchronous machines*, and a stoppage of any individual workhead causes the whole machine to stop. In the other group of machines, which are known as *free-transfer* or *nonsynchronous assembly machines*, the workheads are separated by buffers containing assemblies, and transfer to and from these buffers occurs when the particular workhead has completed its cycle of operations. Thus, with a free-transfer machine, a fault or stoppage of a workhead will not necessarily prevent another workhead from operating, because a limited supply of assemblies will usually be available in the adjacent buffers.

One of the principal problems in applying automation to the assembly process is the loss in production resulting from stoppages of automatic workheads when defective component parts are fed to the machine. With manual workstations on an assembly line, the assembly workers are able to discard defective parts quickly, with little loss of production. However, a defective part fed to an automatic workhead can, on an indexing machine, cause a stoppage of the whole machine, and production will cease until the fault is corrected. The resulting downtime can be very high with assembly machines having several automatic workheads. This can result in a serious loss in production and a consequent increase in the cost of assembly. The quality levels of the parts to be used in automatic assembly must, therefore, be considered when an assembly machine is designed.

In the following sections, a study is made of the effects of the quality levels of parts on the performance and economics of assembly machines.

6.1 INDEXING MACHINES

6.1.1 Effect of Parts Quality on Downtime

In the following analysis, it will be assumed that an indexing machine having n automatic workheads and operating with a cycle time of t sec is fed with parts having, on average, a ratio of defective parts to acceptable parts of x. It will also be assumed that a proportion m of the defective parts will cause machine stoppages and, further, that it will take an operator T sec, on average, to locate the failure, remove the defective part, and restart the machine.

With these assumptions, the total downtime due to stoppages in producing N assemblies will be given by $mxnNT$. Each time the machine indexes, all assembly tasks are completed and one assembly is delivered from the machine; hence, the machine time to assemble N assemblies is Nt sec and, thus, the proportion of downtime D on the machine is given by

$$\begin{aligned} D &= \frac{\text{downtime}}{\text{assembly time} + \text{downtime}} \\ &= \frac{mxnNT}{Nt + mxnNT} = \frac{mxn}{mxn + t/T} \end{aligned} \tag{6.1}$$

In practice, a reasonable value of the machine cycle time t would be 6 sec, and experience shows that a typical value for the average time taken to clear a fault is 30 sec. With these figures, the ratio t/T will be 0.2, and Figure 6.1 shows the effect of variations in the mean quality level of the parts on the downtime for indexing machines with 5, 10, 15, and 20 automatic workheads. (It is assumed in this example that all defective parts will produce a stoppage of the machine and, thus, $m = 1$.)

For standard fasteners such as screws, which are often employed in assembly processes, an average value for x might be between 0.01 and 0.02. In other words, for every 100 acceptable screws, there would be between one and two defective ones. A higher quality level is generally available, but with screws, for example, a reduction of x to 0.005 may double their price and seriously affect the cost of the final assembly. It will be seen later that a typical economic value for x is 0.01, and Figure 6.1 shows that, with this value, the downtime on an assembly machine having 10 automatic workheads is 0.33 of the total time available. These results show why it is rarely economical to use indexing machines having a large number of automatic workheads. They also illustrate why, in practice, it is advisable to allow for downtime when considering the use of an indexing assembly machine.

6.1.2 Effects of Parts Quality on Production Time

In the preceding example, it was assumed that all the defective parts fed to the automatic workheads would stop the machine (that is, $m = 1$ in Equation 6.1). In practice, however, some of these defective parts would pass through the feeding devices and automatic workheads, but would not be assembled correctly and would result in the production of an unacceptable assembly. In this case, the effect of the defective part would be to cause downtime on the machine equal to only one machine cycle. The time taken to produce N assemblies, whether these are acceptable or not, is given by $(Nt + mxnNT)$ and, if $m < 1$, only about $[N - (1\ m)xnN]$ of the assemblies produced will be acceptable. The average production time t_{pr} of acceptable assemblies is therefore given by

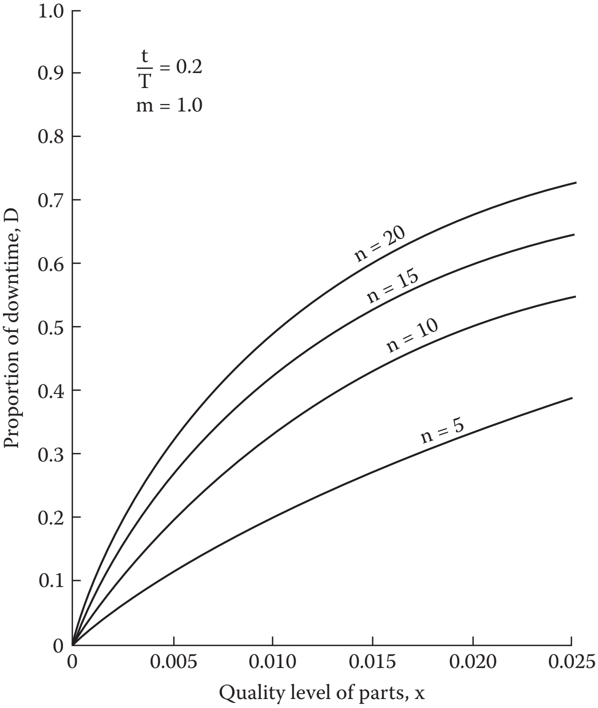


FIGURE 6.1 Effect of parts quality on indexing machine downtime; *n* is the number of automatic workheads, *t* the machine cycle time, *T* the time to correct a machine fault, and *m* the proportion of defective parts causing a machine stoppage.

$$t_{\mathrm{pr}} = \frac{Nt + mxnNT}{N - (1 - m)xnN} = \frac{t + mxnT}{1 - (1 - m)xn} \tag{6.2}$$

Taking typical values of $x = 0.01$, $t = 6$ sec, $T = 30$ sec, and $n = 10$, Equation 6.2 becomes

$$t_{\mathrm{pr}} = \frac{30(2 + m)}{9 + m} \tag{6.3}$$

Equation 6.3 is plotted in Figure 6.2 to show the effect of m on t_{pr}, and it can be seen that, for a maximum production rate of acceptable assemblies, m should be as small as possible. In other words, when designing the workheads for an indexing assembly machine when a high production rate is required, it is preferable to allow a defective part to pass through the feeder and workhead and “spoil”

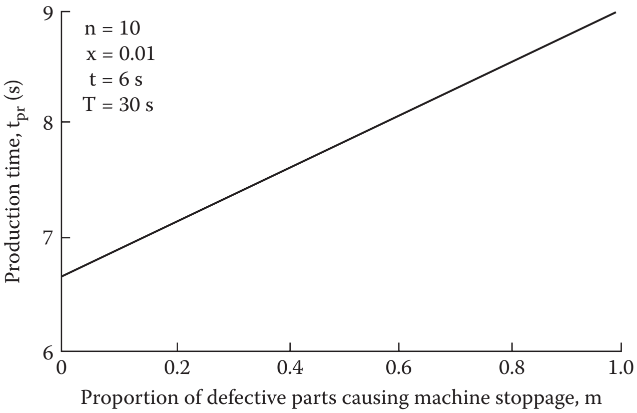


FIGURE 6.2 Variation in production time t_{pr} with changes in the proportion of defective parts causing a machine fault; n is the number of automatic workheads, x the ratio of defective to acceptable parts, t the machine cycle time, and T the time to correct a machine fault.

the assembly rather than allow it to stop the machine. However, in practical circumstances, the cost of dealing with the unacceptable assemblies produced by the machine must be taken into account, and this will be considered later.

For the case in which the defective parts always stop the machine, m is equal to 1, and Equation 6.2 becomes

$$t_{pr} = t + xnT \tag{6.4}$$

Figure 6.3 now shows how the production rate ($1/t_{pr}$) is affected by changes in nominal machine rate ($1/t$) for various values of x and for typical values of T = 30 sec and n = 10. It can be seen that, when x is small, the production rate approaches the machine speed. However, in general, x will lie within the range 0.005–0.02 and, under these circumstances, it can be seen that for high machine speeds (short cycle times), the production rate tends to become constant. Alternatively, it may be stated that, as the cycle time is reduced for otherwise constant conditions, the proportion of downtime increases, and this results in a relatively small increase in the production rate. This explains why it is rarely practicable to have indexing assembly machines working at very high speeds.

6.1.3 EFFECT OF PARTS QUALITY ON THE COST OF ASSEMBLY

The total cost C_t of each acceptable assembly produced on an assembly machine (in which each workhead assembles one part) is given by the sum of the costs of the individual parts $C_1 + C_2 + C_3 + \ldots + C_n$ plus the cost of operating the machine for the average time taken to produce one acceptable assembly. Thus,

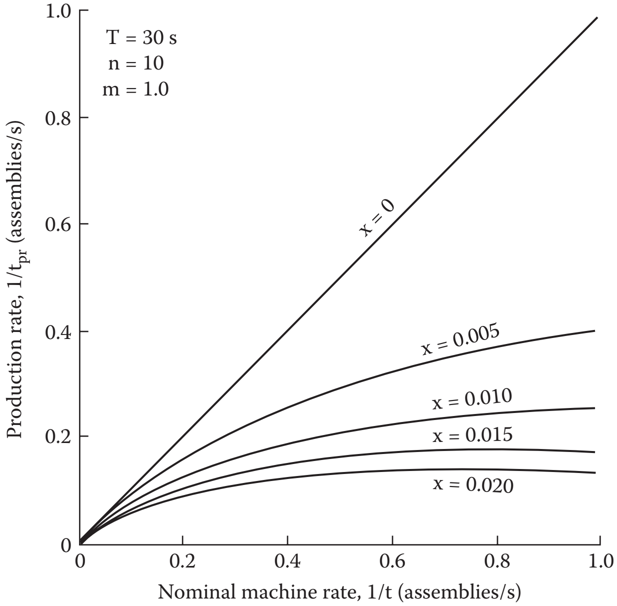


FIGURE 6.3 Effect of parts quality level on indexing machine production rate; *n* is the number of automatic workheads, *T* the time to correct a machine fault, and *m* the proportion of defective parts causing a machine stoppage.

$$C_t = M_t t_{\text{pr}} + C_1 + C_2 + C_3 + \ldots + C_n \tag{6.5}$$

where M_t is the total cost of operating the machine per unit time and includes operators' wages, overhead charges, actual operating costs, machine depreciation, and the cost of dealing with the unacceptable assemblies produced, and t_{pr} is the average production time of acceptable assemblies and may be obtained from Equation 6.2.

In estimating M_t, it will be assumed that a machine stoppage caused by a defective part will be cleared by one of the operators employed on the machine and that no extra cost will be entailed other than that due to machine downtime. Further, it will be assumed that if a defective part passes through the workhead and spoils an assembly, it will take an extra assembly worker t_c sec to dismantle the assembly and replace the nondefective parts in the appropriate feeding devices.

Thus, the total operating cost M_t is given by

$$M_t = M + P_u t_c W_a \tag{6.6}$$

where M is the cost of operating the machine per unit time if only acceptable assemblies are produced and W_a is the assembly worker's rate, including overhead. The number of unacceptable assemblies produced per unit time is denoted by P_u and is given by

$$P_u = \frac{(1-m)xn}{t+mxnT} \tag{6.7}$$

Substitution of Equation 6.7 in Equation 6.6 gives

$$M_t = M + \frac{(1-m)xnt_cW_a}{t+mxnT} \tag{6.8}$$

In estimating the cost C_i of an individual component part, it will be assumed that this can be broken down into (1) the basic cost of the part, irrespective of quality level, and (2) a cost that is inversely proportional to x and that will therefore increase for better-quality parts. Thus, the cost of each part may be expressed as

$$C_i = A_i + \frac{B}{x} \tag{6.9}$$

In this equation, B is a measure of the cost due to quality level and, for the purposes of the present analysis, will be assumed to be constant regardless of the basic cost A_i of the parts.

If Equation 6.2, Equation 6.8, and Equation 6.9 are now substituted into Equation 6.5, the total cost C_t of each acceptable assembly becomes, after rearrangement,

$$C_t = \frac{M(t+mxnT)+(1-m)xnt_cW_a}{1-(1-m)xn} + \sum_{i=1}^{n} A_i + \frac{nB}{x} \tag{6.10}$$

Equation 6.10 shows that the total cost of an assembly can be broken down as follows:

1. A cost that will decrease as x is reduced
2. A cost that is constant
3. A cost that will increase as x is reduced

It follows that, for a given situation, an optimum value of x will exist that will give a minimum cost of assembly. For the moment, the optimum value of x will be considered for the case in which $m = 1$ (that is, where all defective parts cause a stoppage of the machine).

With $m = 1$, Equation 6.10 becomes

$$\underset{\substack{\text{cost of}\\ \text{assembly}\\ \text{operations}}}{C_t = Mt} + \underset{\substack{\text{cost of}\\ \text{downtime}}}{MxnT} + \underset{\substack{\text{cost of}\\ \text{parts}\\ \text{quality}}}{\frac{nB}{x}} + \underset{\substack{\text{basic}\\ \text{cost of}\\ \text{parts}}}{\sum_{i=1}^{n} A_i} \tag{6.11}$$

Equation 6.11 is now differentiated with respect to x and set equal to zero, yielding the following expression for the optimum value of x, giving the minimum cost of assembly:

$$x_{\text{opt}} = \left(\frac{B}{MT}\right)^{1/2} \tag{6.12}$$

It is interesting to note that, for a given assembly machine, where M and B are constants, the optimum quality level of the parts used is dependent only on the time taken to clear a defective part from a workhead.

Figure 6.4 shows how the cost of a part might increase as the quality level is improved. In this case, A_i = \$0.002 and B = \$0.00003. If typical values of M = 0.01 \$/sec (36 \$/h) and T = 30 sec are now substituted in Equation 6.12, the corresponding optimum value of x is 0.01 (1%). Equation 6.12 may now be substituted in Equation 6.11 to give an expression for the minimum cost of assembly:

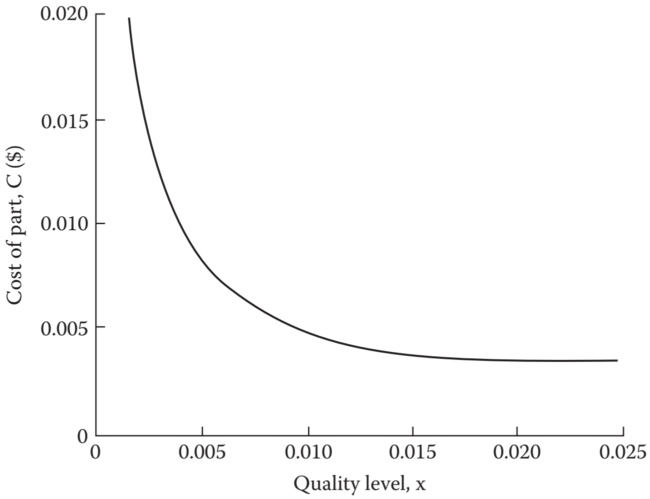


FIGURE 6.4 Typical relationship between part quality and cost.

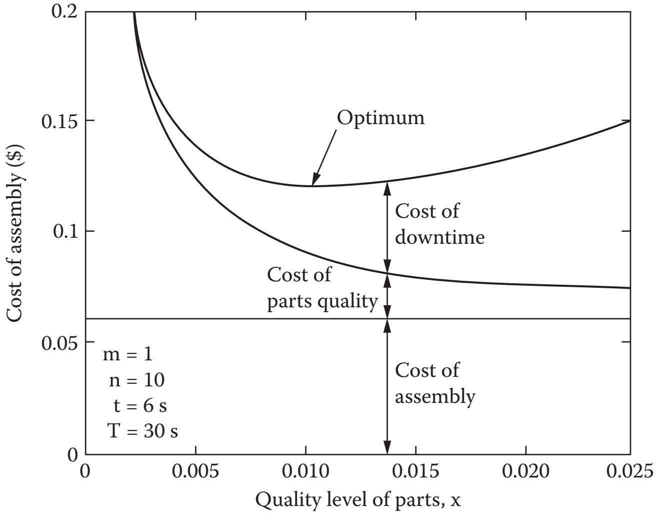


FIGURE 6.5 Effect of parts quality level on assembly costs.

$$C_t(\min) = Mt + 2n(MBT)^{1/2} + \sum_{i=1}^{n} A_i \tag{6.13}$$

With $t = 6$ sec and $n = 10$, the cost of assembling each complete set of parts (the first two terms in Equation 6.13) would be \$0.12. Half this cost would be attributable to the assembly operation itself, and the other half to the increased cost due to parts quality and the corresponding cost of machine downtime. Figure 6.5, where the first three terms in Equation 6.11 are plotted, shows how these individual costs would vary as the quality level x varies, using the numerical values quoted in the example above. In this case, if parts having 0.02 defective were to be used instead of the optimum value of 0.01, the cost of assembly would increase by approximately 12%. This is a variation of \$0.015 per assembly and, with an average production time of 9 sec (calculated from Equation 6.2), it represents an extra expense of approximately \$12,000/year per shift.

In the analysis above, it was assumed that all defective parts would stop the machine. If, instead, it were possible to allow these parts to pass through the automatic devices and spoil the assemblies, the cost of assembly could be obtained by substituting $m = 0$ into Equation 6.10. Thus,

$$C_t = \frac{Mt + xnt_cW_a}{1 - xn} + \sum_{i=1}^{n} A_i + \frac{nB}{x} \tag{6.14}$$

Again, an optimum value of x arises and is found by differentiation of Equation 6.14 to be

$$x_{\text{opt}} = \left[n + \left(\frac{t_c W_a}{B} + \frac{Mt}{B} \right)^{1/2} \right]^{-1} \tag{6.15}$$

Taking W_a = \$0.002/sec, t_c = 60 sec, and the remaining figures as before, x_{opt} is found to be approximately 0.011. From Equation 6.14, the minimum cost of assembly is \$0.109, which represents a saving of 9% on the cost of assembly compared to the preceding example.

It is possible to draw two main conclusions from the examples discussed. First, for the situation analyzed, it would be preferable to allow a defective part to pass through the workhead and spoil the assembly rather than to allow it to stop the indexing machine. This would not only increase the production rate of acceptable assemblies but would also reduce the cost of assembly. Second, an optimum quality level of parts always exists that will give minimum cost of assembly.

6.2 FREE-TRANSFER MACHINES

A free-transfer or nonsynchronous machine always gives a higher production rate than the equivalent indexing machine. This is because the buffers of assemblies available between workheads will, for a limited time, allow the continued operation of the remaining workheads when one has stopped. Provided that the buffers are sufficiently large, the stopped workhead can be restarted before the other workheads are affected, and the downtime on the machine approaches the downtime on the workhead that has the most stoppages. The following analysis shows that, even with relatively small buffers, the production rate of the machine can be considerably higher than that obtained with the equivalent indexing machine.

It is assumed in the analysis that all the workheads on a free-transfer machine are working at the same cycle time of t seconds. Each workhead is fed with parts having the same quality level of x (where x is the ratio of defective to acceptable parts), and between each pair of workstations is a buffer that is large enough to store b assemblies. Any workhead on a free-transfer assembly machine will be forced to stop under three different circumstances:

1. A defective part is fed to the workhead and prevents the completion of its cycle of operations. In this case it will be assumed that an interval of T sec elapses before the fault is cleared and the workhead restarted.
2. The adjacent workhead up the line has stopped, and the supply of assemblies in the buffer storage between is exhausted.
3. The adjacent workhead down the line has stopped, and the buffer between is full.

Consideration of these last two circumstances leads to the conclusion that spaces in buffers cause the same problems as assemblies in buffers. Thus, to optimize the performance of a free-transfer machine, the number of spaces in buffers should be made equal to the number of assemblies in buffers. In other words, the buffers should be half filled with assemblies. It will therefore be assumed that, at any time, the buffer between any two workheads is half filled. Of course, this will rarely be the case and, in fact, for half the time, the buffer will be empty and, for the remaining time, it will be full. In the following analysis, the assumption that any particular buffer will be half filled with assemblies will, therefore, lead to an underestimation of the downtime caused by workhead faults.

Thus, if two adjacent workheads have $b/2$ assemblies in the buffer storage between them, then a fault in the first workhead will prevent the second from working after a time delay of $bt/2$ sec. A fault in the second workhead will prevent the first from working after the same time. Also, over a long period, the average downtime on each workhead must be the same. It will also be assumed that when a fault occurs, there will always be a technician available to correct it and that no workhead will stop while another is stopped. The errors resulting from this latter assumption will become large when the quality level of the parts is poor (large x) and when the number of automatic workheads is large (large n). However, specimen calculations show that these errors are negligible with practical values of x and n and produce an overestimate of the machine downtime.

6.2.1 PERFORMANCE OF A FREE-TRANSFER MACHINE

For a typical workhead on a free-transfer machine (Figure 6.6) producing N assemblies, Nx stoppages will occur if m is unity. If each fault takes T sec to correct, the downtime on the first workhead due to its own stoppages is given by NxT. This same average downtime will apply for stoppages on the second workhead down the line, but the first will be prevented from working only for a period of $Nx[T - bt/2]$ sec. Similarly, stoppage of the third workhead will prevent the first from working only for a period of $Nx[T - bt]$ sec. The same expressions can be derived for the effects of the second and third workheads up the line. Thus, it can be seen that the total downtime d on any workhead while the machine produces N assemblies is given by

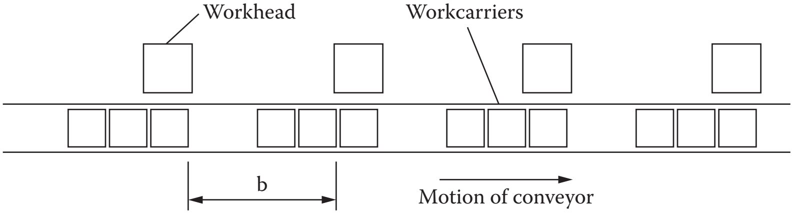


FIGURE 6.6 Free-transfer machine showing the average situation during operation.

$$\frac{d}{Nx} = \ldots \left[T - \frac{3bt}{2}\right] + \left[T - bt\right] + \left[T - \frac{bt}{2}\right] +$$

$$T + \left[T - \frac{bt}{2}\right] + \left[T - bt\right] + \left[T - \frac{3bt}{2}\right] + \ldots$$

or

$$\frac{d}{Nx} = T + \left[2T - bt\right] + \left[2T - 2bt\right] + \left[2T - 3bt\right] + \ldots \qquad (6.16)$$

It should be noted that if any term in square brackets is negative, it should be omitted. It is necessary at this stage to know the relative values of T and t. If, for example, the ratio T/t is 5 and $b = 4$, Equation 6.16 becomes

$$\frac{d}{Nx} = 5T - 3bt \qquad (6.17)$$

or

$$d = 13Nxt \qquad (6.18)$$

The proportion of downtime D on the machine may now be obtained as follows:

$$D = \frac{\text{downtime}}{\text{assembly time} + \text{downtime}} = \frac{d}{Nt + d} \qquad (6.19)$$

and substitution of d from Equation 6.18 gives

$$D = \frac{13xt}{t + 13xt} \qquad (6.20)$$

For different values of b, other bracketed terms in Equation 6.16 will become zero or negative, and new values of d will be obtained.

In general, the machine downtime d may be expressed as

$$d = KNxt \qquad (6.21)$$

where K is a factor that depends on the values of T/t and b. Table 6.1 gives the values of K for various values of b when $T/t = 5$.

TABLE 6.1
Relationship between Buffer Capacity *b* and the Factor *K*

b	*K*
0	25
2	19
4	13
6	9
8	7
10	5

The proportion of downtime D is now given by

$$D = \frac{d}{Nt + d} = \frac{Kx}{1 + Kx} \tag{6.22}$$

For b≥ 10, all bracketed terms are omitted from Equation 6.16, and the equation for the downtime on each workhead becomes

$$\frac{d}{Nx} = T \tag{6.23}$$

The downtime on the machine equals the downtime on any workhead and, thus, for $b \geq 10$,

$$D = \frac{5x}{1 + 5x} \tag{6.24}$$

Figure 6.7 shows how the proportion of downtime is affected by the size of the buffers for $x = 0.01$ and for machines with 5, 11, 21, and 41 stations. It can be seen that significant improvements in performance can be obtained with only small buffers, especially with large machines. Also, with large buffers, the machine downtime is independent of the machine size and approaches the downtime on a single station when it is unaffected by stoppages at other stations.

In theory, when the size of the buffer storage b is greater than or equal to $2T/t$, the workheads are completely isolated from each other, and further increases in the size of b have no effect. However, the greatest benefit occurs with the smaller buffers. Therefore, as a practical guide, it is often assumed that for a good free-transfer assembly machine design, b equals T/t.

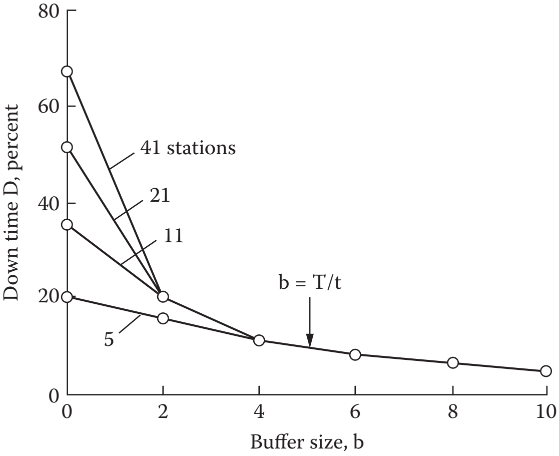


FIGURE 6.7 Theoretical effect of buffer storage size on proportion of downtime for several free-transfer machines.

It should be pointed out that the method of analysis for free-transfer machines presented in this chapter is only approximate, although the results of computer simulations presented in Figure 6.8 for the same conditions as those in Figure 6.7 show that the analysis gives a good approximation to the true performance of a machine when $b \leq T/t$.

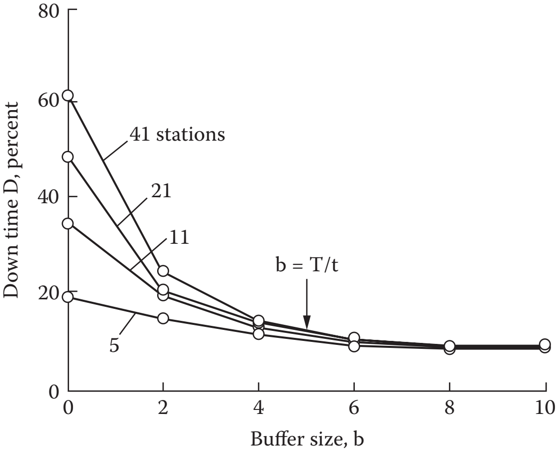


FIGURE 6.8 Results of computer simulations showing the effect of buffer storage on downtime for several free-transfer machines. (From Boothroyd, G. and Dewhurst, P., Design for Assembly Software Toolkit, Boothroyd Dewhurst, Wakefield, RI, 1990. With permission.)

6.2.2 AVERAGE PRODUCTION TIME FOR A FREE-TRANSFER MACHINE

When considering the economics of free-transfer machines, the cost of providing the buffers has to be taken into account. Ideally, it is necessary to develop a mathematical model in which the size b of the buffers between each station is a variable and then to study how the assembly costs C_{pr} are affected by the magnitude of b. However, later analysis will show that when the number of parts to be assembled, n, is small, the free-transfer machine is uneconomical compared to an indexing machine. When n is large, the reverse is true. Thus, when n is small, the optimum value of b is zero (representing an indexing machine) and, when n is large, the optimum value is close to that at which the various workheads do not affect one another significantly. Inspection of Figure 6.7 and Figure 6.8, which show the effect of buffer size on the proportion of downtime, indicates that when $b \geq 10$, the proportion of downtime D on the machine approaches that of a single isolated workhead. In general, this is true if $b \geq 2T/t$, where T is the downtime due to one defective part and t is the workhead cycle time. However, analysis of the economics of individual machines shows that a value of b equal to T/t results in cost savings closely approaching those for $b = 2T/t$ and, therefore, to simplify analysis and to make rough cost comparisons, it will be assumed that on a free-transfer machine, $b = T/t$ and that the resulting downtime for the machine approaches a value twice that for an individual isolated station (Figure 6.7 and Figure 6.8).

Hence, for a free-transfer machine of any size, the average production time can be estimated from

$$t_{\mathrm{pr}} = t + 2xT \tag{6.25}$$

where x is the parts quality level. It is, of course, assumed here that all defective parts will cause a stoppage of the workhead. Thus, Equation 6.25 can be compared with Equation 6.4 for an indexing machine.

6.2.3 NUMBER OF PERSONNEL NEEDED FOR FAULT CORRECTION

In the computer simulations, the assembly machines were provided with an excess of personnel so that all faults caused by defective parts would receive immediate attention. However, the number of personnel needed in order to achieve this situation on large systems would be uneconomical, and it would be better to allow some faults to go unattended for a short time in order to increase the utilization of the lesser number of personnel. Clearly, for optimum working, the number of personnel required will be proportional to the number of stations on the machine.

During the production of N assemblies, each containing n parts automatically assembled, and with each part having x defectives causing faults, the total faults will be given by Nxn, and the total time spent by personnel correcting faults will be $NxnT$, where T is the average time to correct each fault. Because the total production time on a free-transfer machine is given by Equation 6.25, the minimum number of technicians N_{tech} required to correct faults is given by

$$\begin{aligned} N_{\text{tech}} &= \frac{\text{total fault correction time}}{\text{total production time}} \\ &= \frac{NxnT}{N(2xT + t)} \\ &= \frac{xn}{2x + t/T} \end{aligned} \tag{6.26}$$

Alternatively, the maximum number of stations $n_{s\,\max}$ that one technician can tend is given by

$$n_{s\,\max} = \frac{n}{N_{\text{tech}}} = 2 + \frac{t}{xT} \tag{6.27}$$

Using $t/T = 0.2$ and $x = 0.01$, Equation 6.27 would show that one technician could tend no more than 22 stations on a free-transfer machine having these characteristics. However, because faults can occur on a free-transfer machine while an earlier fault is still being corrected, the number of stations per technician will be less than that given by Equation 6.27. Figure 6.9 shows that the optimum number of stations is closer to 16. Thus, Equation 6.27 could be modified to give the economical number of stations per technician as follows:

$$n_s = 2 + \frac{2t}{3xT} \text{ approximately} \tag{6.28}$$

With an indexing machine, any fault causes the whole machine to stop and, therefore, no more than one technician, theoretically, would be needed to correct faults.

We shall now use these results to compare the economics of various assembly systems.

6.3 BASIS FOR ECONOMIC COMPARISONS OF AUTOMATION EQUIPMENT

In simple analyses of the economics of automation equipment, it is advantageous to convert the capital cost of the equipment to an equivalent assembly worker rate. For this purpose, a factor Q_e can be defined as the cost of the capital equipment that can economically be used to do the work of one assembly worker on one shift [2,3]. This figure, which must be determined for a particular company,

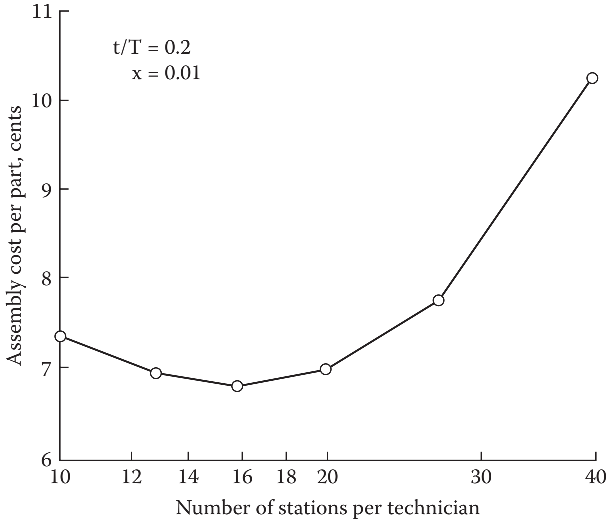


FIGURE 6.9 Effect of number of technicians available to clear faults on a free-transfer machine (from computer simulation).

is the basis for the following economic comparisons. For example, if a simple piece of automation equipment is being considered and it can do the job of one assembly worker, then the economical cost of the equipment would be Q_e for one-shift working, $2Q_e$ for two-shift working, etc. The rate for a piece of equipment initially costing C_e is then given by $C_e W_a/(S_n Q_e)$, where W_a is the rate for one assembly worker and S_n the number of shifts. In fact, many companies determine Q_e by multiplying the annual cost of an assembly worker by a factor that usually lies between 1 and 3, representing a payback period of 1–3 years.

6.3.1 Basic Cost Equations

The cost of assembly C_a for a complete assembly is given by

$$C_a = t_{\text{pr}} \left[W_t + \frac{C_e W_a}{S_n Q_e} \right] \tag{6.29}$$

where t_{pr} is the average time between delivery of complete assemblies for a fully utilized system, W_t the total rate for the machine personnel, and C_e the total capital cost for all equipment, including engineering setup and debugging cost.

For the purpose of comparing the economics of assembly systems, the cost of assembly per part will be used and will be nondimensionalized by dividing this cost per part by the rate for one assembly worker W_a and the average manual assembly time per part t_a. Thus, the dimensionless assembly cost per part C_d is given by

$$C_d = \frac{C_a}{nW_a t_a} \tag{6.30}$$

Substitution of Equation 6.29 into Equation 6.30 gives

$$C_d = \left(\frac{t_{\mathrm{pr}}}{t_a}\right) \square \left(W_r + \frac{C_e}{nS_n Q_e}\right) \tag{6.31}$$

where

$$W_r = \frac{W_t}{W_a n} \tag{6.32}$$

and is the ratio of the cost of all personnel compared with the cost of one manual assembly worker, expressed per part in the assembly. Thus, the dimensionless assembly cost per part for an assembly worker working without any equipment will be unity, which forms a useful basis for comparison purposes.

Finally, it should be pointed out that, for a particular assembly machine, Equation 6.31 holds true only if the required average production time t_q for one assembly is greater than or equal to the minimum production time t_{pr} obtainable for the machine. In other words, if $t_{\mathrm{pr}} \leq t_q$, then t_q must be substituted for t_{pr} in Equation 6.31 because the machine is not fully utilized. If $t_{\mathrm{pr}} > t_q$, then more than one machine will be needed to meet the required production rate. Now, for example, two machines producing N assemblies/hr will give the same assembly costs per assembly as one machine producing $N/2$ assemblies/hr. Hence, it will be assumed that, as the average required production time for one assembly t_q is reduced below the production time t_{pr} obtainable from one machine, the assembly costs become constant and are given by Equation 6.31. To obtain t_q, it is necessary to know the required annual production volume per shift V_s and the plant efficiency P_e, the latter being defined as the time actually worked in the plant divided by the time available. Thus,

$$t_q = \frac{0.072P_e}{V_s} \tag{6.33}$$

In this formula, t_q is given in seconds, V_s is in millions, P_e is expressed as a percentage, and the factor 0.072 arises from the assumption that 7.2 msec is the maximum time available in one shift-year.

We have now established the basic cost equations necessary to compare the economics of assembly systems using the capital equivalent of assembly worker costs.

6.4 COMPARISON OF INDEXING AND FREE-TRANSFER MACHINES

In analyzing the economics of special-purpose assembly machines, the following nomenclature will be used, and the numerical values given in parentheses represent the estimates of the cost of the equipment used in the later comparisons:

C_T = cost of transfer device per workstation for an indexing machine (\$10k)
C_B = cost of transfer device per space (workstation or buffer space) for a free-transfer machine (\$5k)
C_C = cost of work carrier (\$1k)
C_F = cost of automatic feeding device and delivery track (\$7k)
C_W = cost of workhead (\$10k)
W_{tech} = rate for one technician engaged in correcting faults on the machine (\$0.012/sec)
W_a = rate for one assembly worker (\$0.008/sec)
Q_e = equivalent cost of one assembly worker in terms of capital investment (\$90k)
t_a = average manual assembly time per part (8 sec)

It should be noted that equipment costs include the purchase costs, the assembly machine design, engineering and debugging costs, the costs of controls, and so on. It has been estimated [4] that purchase cost often forms only 40% of the total cost of equipment.

6.4.1 INDEXING MACHINE

For an indexing machine, the total equipment cost C_e will be given by

$$C_e = n(C_T + C_W + C_F + C_C) \tag{6.34}$$

Assuming two assembly workers to load and unload assemblies, the total rate for the personnel will be

$$W_t = 2W_a + W_{\text{tech}} \tag{6.35}$$

Substituting for C_e from Equation 6.34, for W_t from Equation 6.35, and for t_{pr} from Equation 6.4 into Equation 6.31 gives, for the dimensionless cost of assembly per part,

$$C_d = \frac{\left(t + xnT\right)\square\left[2 + \frac{W_{\text{tech}}}{W_a} + \frac{n\left(C_T + C_W + C_F + C_C\right)}{S_n Q_e}\right]}{nt_a} \tag{6.36}$$

6.4.2 FREE-TRANSFER MACHINE

For a free-transfer machine, in which the number of work carriers chosen is such that on average the machine will be half full, the total equipment cost C_e will be given by

$$C_e = n\left[C_W + C_F + \left(b+1\right)\square\left(C_B + \frac{C_C}{2}\right)\right] \tag{6.37}$$

Again, assuming two assembly workers to load and unload assemblies and using Equation 6.28, the total rate for the personnel will be

$$W_t = 2W_a + \left(\frac{nW_{\text{tech}}}{2 + \left(2t/3xT\right)}\right) \tag{6.38}$$

Substituting for $b = T/t$, t_{pr} from Equation 6.25, C_e and W_t from Equation 6.37 and Equation 6.38 into Equation 6.31 gives

$$C_d = \left(t + 2xT\right)$$

$$\left\{2 + \left(\frac{nW_{\text{tech}}}{2 + \left(2t/3xT\right)}\right)\left(\frac{1}{W_a}\right) + n\frac{C_W + C_F + \left(1 + T/t\right)\ \left(C_B + C_C/2\right)}{S_n Q_e}\right\} / nt_a \tag{6.39}$$

provided the number of technicians is not less than one. Assuming a cycle time t of 6 sec, a downtime T of 30 sec, a quality level x of 0.01, two-shift working (S_n = 2), and the numerical values of equipment and operator costs described earlier, Figure 6.10 shows for the two machines how the dimensionless cost of assembly per part varies with the size of the machine. It can be seen that for small values of n (small machines), the indexing machine is the more economical of the two, whereas for large values of n the free-transfer machine is the more economical. The rise in costs for the indexing machine is attributable entirely to the increasing downtime as the machine becomes larger. In fact, the dashed region of the curve represents downtime proportions of greater than 50%.

6.4.3 EFFECT OF PRODUCTION VOLUME

Turning now to the effects of production volume, it should first be realized that a special-purpose assembly machine is designed to work at a particular rate. This means that, under normal circumstances, the output can be obtained from a knowledge of t_{pr}, the mean production time obtainable. Thus, the obtainable annual production volume per shift V_s in millions is given by

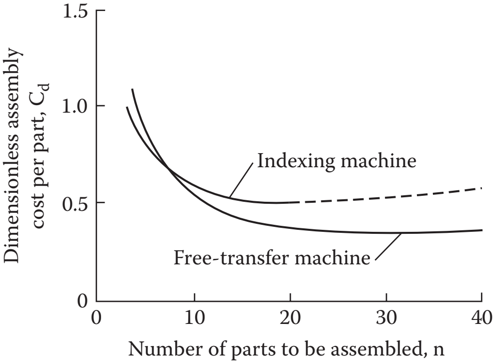


FIGURE 6.10 Comparison of the economics of multistation assembly machines.

$$V_s = 0.072P_e/t_{\text{pr}} \tag{6.40}$$

In this formula, P_e is the plant efficiency (percent) and is defined as the time actually worked in the plant divided by the time available, and it is assumed that 7.2 million sec are available in one shift-year. Thus, on a graph of assembly cost vs. annual production volume such as that shown in Figure 6.11, a special-purpose assembly machine is represented by a single point corresponding to the production volume obtainable from the machine working at maximum capacity. However, for comparison, it is desirable to be able to show the relation between assembly cost and the annual production volume per shift required.

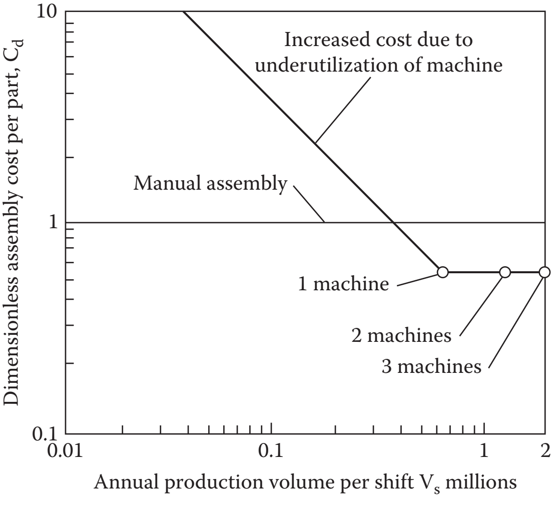


FIGURE 6.11 Assembly costs for an indexing machine with ten stations.

If the volume required is less than that obtainable from the machine, then, as explained earlier, the assembly cost will be a function of the average production time required t_q, which is given by Equation 6.33. In this case, when the assembly costs (given by Equation 6.31) and the annual production volume per shift are plotted on logarithmic scales, a linear relationship results as shown in Figure 6.11. This relationship simply shows how costs increase because the machinery is not being fully utilized.

If the required production volume is greater than that obtainable from the machine, then it is assumed that backup will be provided in the form of manual assembly stations. Then, when the required volume approaches a value twice that obtainable, a second machine will be employed, and so on. Because the assembly cost is independent of the number of assembly machines, the relation between dimensionless assembly cost and volume will be a horizontal line (Figure 6.11) due to the smoothing provided by the use of manual assembly where required.

The multistation assembly machines considered in the preceding text were both assumed to be "dedicated" to one product. However, it should be realized that the output from one machine is on the order of 1–5 million assemblies per year and that application of these systems is limited to mass-production situations in which the product design is stable for a few years. It should also be realized that mass production constitutes only about 15–20% of all production in the U.S. and, for this reason, much attention is being given at present to the possibilities of automating batch assembly processes. It is clear that, for these applications, it will be necessary to employ programmable or flexible automation — in fact, assembly robots.

6.5 ECONOMICS OF ROBOT ASSEMBLY

One of the problems in making general economic comparisons between assembly systems is that, typically, some of the operations required for a particular product cannot be automated; one of the key characteristics of a system is its ability to handle this situation. Accordingly, a study was made [5] in which, by working closely with various key manufacturing organizations, the author was able to determine the kinds of assemblies that were generally considered candidates for robot assembly. It was found that these assemblies have similar characteristics and that a typical profile could be deduced for a candidate assembly. Using this typical candidate assembly, the economics of some configurations of robot assembly systems were considered. The following discussion will be restricted to those situations in which general-purpose assembly robots can be applied, and three basic systems will be modeled. These systems are:

1. A single-station machine with one fixture and one robot arm (Figure 6.12)
2. A single-station machine with one fixture and two robot arms (Figure 6.13)

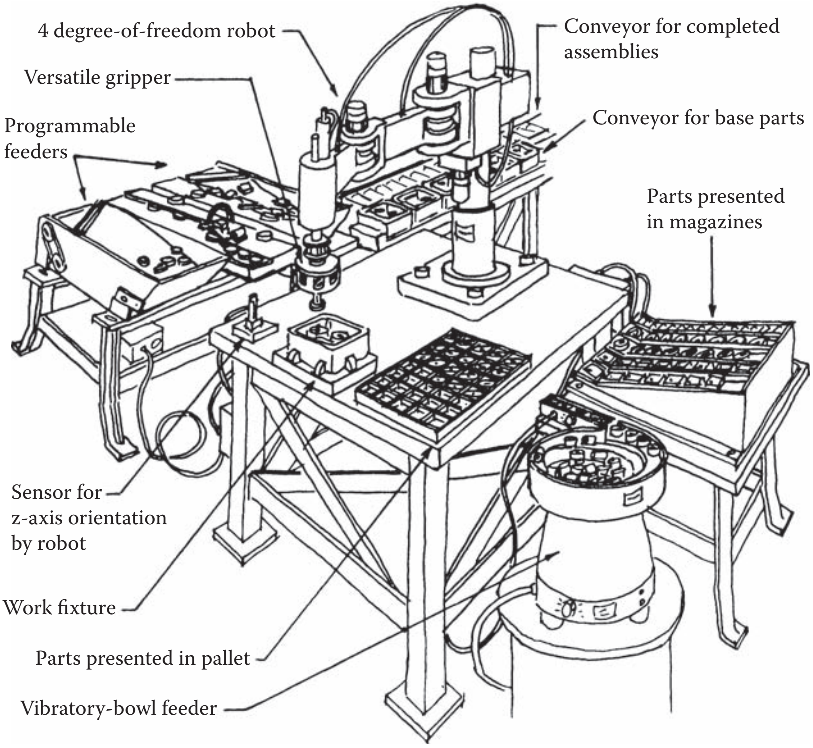

4 degree-of-freedom robot
Versatile gripper
Programmable feeders
Conveyor for completed assemblies
Conveyor for base parts
Parts presented in magazines
Sensor for z-axis orientation by robot
Work fixture
Parts presented in pallet
Vibratory-bowl feeder

FIGURE 6.12 Single-station assembly system with one robot arm.

3. A multistation free-transfer machine with single robot arms at the various stations where appropriate (Figure 6.14)

6.5.1 PARTS PRESENTATION

When the suitability of products for robot assembly is determined, it is important to consider the available methods of parts presentation. These range from "bin-picking," using the most sophisticated vision systems, to the manual loading of parts into pallets or trays.

Much research has been conducted on the subject of programmable feeders, and the impression is given that these can be used for systems that can assemble a variety of products. However, investigations have shown that most, if not all, of the "programmable" assembly systems developed in the U.S. will be devoted to the assembly of one product or one family of products. Thus, these systems will be flexible in the sense that they can be adjusted quickly to accommodate different members of the product family (different styles) or to accommodate product design changes. Nevertheless, the equipment used on these systems will be dedicated to the product family, regardless of whether it is special-purpose equipment or programmable equipment.

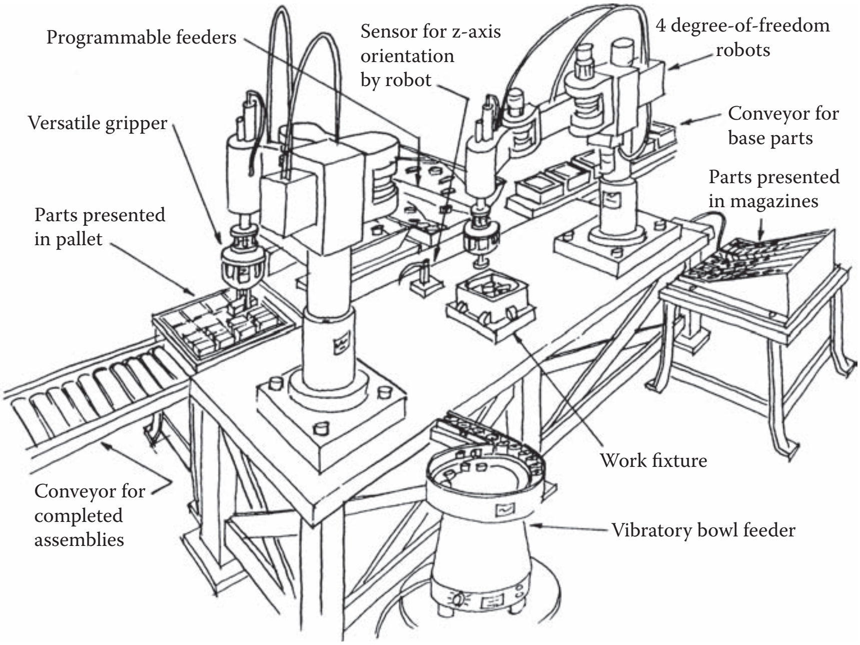

Programmable feeders
Sensor for z-axis orientation by robot
4 degree-of-freedom robots
Versatile gripper
Conveyor for base parts
Parts presented in magazines
Parts presented in pallet
Work fixture
Conveyor for completed assemblies
Vibratory bowl feeder

FIGURE 6.13 Single-station assembly system with two robot arms.

When the economic choice of part-presentation method is to be determined, there will usually be only two basic types to consider:

1. Those involving manual handling and loading of individual parts into part trays, pallets, or magazines
2. Those involving automatic feeding and orienting of parts from bulk

In some cases, it is possible to obtain parts premagazined. Because these magazines have usually been filled by hand or automatically from bulk, the cost of the magazining must be included in the cost of the parts. Thus, the economics of using premagazined parts will have to be considered on a case-by-case basis with a knowledge of the increased parts costs.

For the present purposes, no distinction will be made between different types of automatic equipment, because the cost of feeding each part automatically, C_f, will be given by multiplying the rate for the equipment (cents/sec) by the time interval between which parts are required. Hence,

$$C_f = \frac{C_F W_a}{S_n Q_e} t_{\text{at}} \tag{6.41}$$

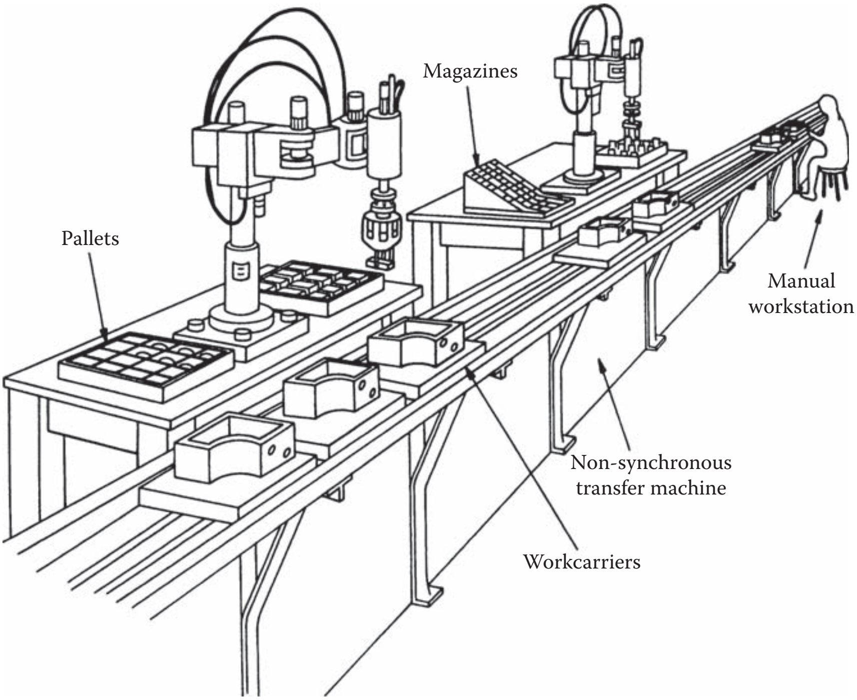


FIGURE 6.14 Multistation free-transfer system utilizing robot arms where appropriate.

where C_f is the cost of feeding one part (cents); C_F the cost of the feeder for one part type, including tooling, engineering, debugging (in thousands of dollars); and t_{at} the average station cycle time (sec).

The cost C_{mm} of using a manually loaded magazine to present one part will be given by

$$C_{\mathrm{mm}} = (C_M W_a / S_n Q_e) t_{\mathrm{at}} + W_a t_m \tag{6.42}$$

where C_M is the cost of the magazines (in thousands of dollars), t_m the manual handling and insertion time for loading one part into the magazines (sec), and W_a the assembly worker rate (cents/sec).

For a simple part, the value of t_m is approximately 2 sec. A typical value of W_a is 0.8 cents/sec.

It will be assumed that a vibratory-bowl feeder, when supplied with simple tooling, engineered, debugged, and fitted with the necessary delivery track, costs $7000 and that the cost of a special-purpose magazine or feed track is $1000. If, as before, $S_n = 2$ and $Q_e = 90$, the comparison of part-presentation costs shown in Figure 6.15 is obtained.

It can be seen that the special-purpose feeder would be more economical than the manual loading of magazines for station cycle times less than about 60 sec.

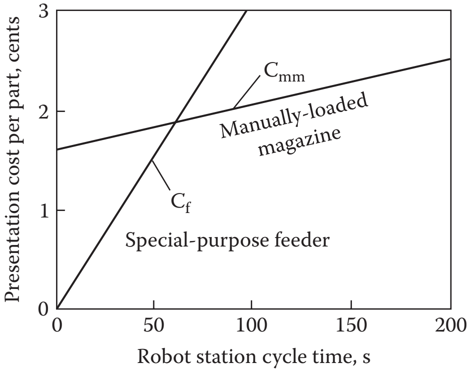


FIGURE 6.15 Comparison of part-presentation costs for robot assembly.

Also, for longer cycle times, the use of feeding equipment rapidly becomes exorbitant.

6.5.2 PROFILE OF TYPICAL CANDIDATE ASSEMBLY

In the study mentioned earlier [5], companies known to be interested in robotic assembly were requested to submit examples of assemblies they considered possible candidates for robotic assembly. Analysis of 12 assemblies indicated that if *n* were the total number of parts, then:

1. 0.78*n* were different part types. This would approximate the case, for example, in which, in an assembly containing ten parts, three were identical. Information such as this is important because, for example, in a single-station machine using one arm, these three parts could all be presented by the same feeder.
2. 0.22*n* parts could be assembled automatically but not fed automatically, and required manual handling. Such parts would be manually loaded into pallets, magazines, or feed tracks.
3. 0.71*n* parts could be fed and oriented using 0.5*n* special-purpose feeders.
4. 0.12*n* parts required manual handling and insertion or some manual manipulation. On a transfer machine, these would require a separate manual station. On a single-station system, the partially completed assemblies would be delivered to a manual station external to the system and then returned to the system after completion of the manual operation. Thus, two pick-and-place operations involving a robot arm would be required in addition to the manual operation.
5. 0.18*n* parts required special grippers or tools in addition to the basic grippers.

6. $0.15n$ parts required that the assembly be transferred to a special-purpose workhead or tool to complete the required operation.
7. The average assembly time per part for a single-station assembly system with one fixture and two robot arms was 3.29 sec; for a system with one arm, it was 5.4 sec.
8. If the product were to be manually assembled, the average assembly time per part would be 8.15 sec.

Using these figures, it is possible to estimate the cost of assembly using different configurations of robot assembly systems and to compare the results with the cost of manual assembly.

6.5.3 SINGLE-STATION SYSTEMS

6.5.3.1 Equipment Costs

First, considering a single-station system with one work fixture and one arm, the costs of the assembly equipment for an assembly containing *n* parts are listed in Table 6.2.

Summing these costs gives the total system cost,

$$C_{e1} = 110 + 5.72n \tag{6.43}$$

Similarly, the cost of a single-station system with one work fixture and two robot arms is found to be

$$C_{e2} = 165 + 6.62n \tag{6.44}$$

TABLE 6.2
Breakdown of Equipment Costs for a One-Arm Single-Station System to Assemble *n* Total Parts

Item	Number Required	Cost per Unit (in Thousands of Dollars)	Total Cost (in Thousands of Dollars)
Robot arm, sensors, controls, etc.	1	100	100
Work fixture	1	5	5
Standard grippers	1	5	5
Special grippers or tools	$0.18n$	5	$0.9n$
Magazines, pallets, etc.	$0.22n$	1	$0.22n$
Special-purpose feeders	$0.5n$	5	$2.5n$
Manual stations and associated feed tracks	$0.12n$	5	$0.6n$
Special-purpose workheads	$0.15n$	10	$1.5n$

The first term has increased because of the additional robot arm and gripper. The second term has increased because, with a two-arm system, in order to keep the cycle time low, it was found best to share repeated operations between the two arms and to duplicate the parts feeders.

6.5.3.2 Personnel Costs

One of the major problems in modeling automatic assembly systems is how to estimate the cost associated with the technician responsible for tending the machine and clearing stoppages due to faulty parts. On a multistation high-speed assembly machine, faults can occur so frequently that at least one full-time technician will be required who can also maintain adequate supplies of parts in the various automatic feeders. Under these circumstances, assemblies are produced at high rates, and the cost of the technician forms a relatively small portion of the total cost of assembly. However, with a low-speed single-station machine using robot arms, the cost of a full-time technician to tend the machine can constitute more than 50% of the cost of assembly.

For the purposes of this analysis, estimates will be made of the actual manual time involved in producing each assembly. Where parts are loaded into magazines or pallets or must be manually inserted, the total time required will be estimated. It will be assumed that if this total manual time is less than the system cycle time, the assembly worker can be engaged in other tasks unrelated to the particular assembly machine being modeled. Similarly, the time necessary for tending the machine will be estimated, and it will be assumed that the technician can be fully occupied by tending several such machines.

It should be emphasized that these assumptions will give the most optimistic estimates of assembly costs, especially while robot assembly is in the development stage. It can be argued, however, that unless machines are eventually designed that can run with a minimum of attention, they will simply not provide an economical alternative to manual assembly. In fact, if a single-station general-purpose assembly machine were to require one full-time technician then, given assistance in the form of fixtures, etc., that same individual could probably perform the assembly tasks at a rate similar to that of the robot.

6.5.3.3 Parts Quality

If the average time taken to clear a fault and restart the system is T, the number of parts in the assembly is n, and the average proportion of defective parts that will cause a fault is x, then the average production time per assembly t_{pr} will be given by

$$t_{\mathrm{pr}} = t_{\mathrm{at}} + xnT \tag{6.45}$$

where t_{at} is the station cycle time (neglecting the downtime due to defective parts).

6.5.3.4 Basic Cost Equation

Using the basic equation for the dimensionless assembly cost per part (Equation 6.31), we get

$$C_d = \frac{t_{\text{pr}}}{nt_a}\left(\frac{W_t}{W_a} + \frac{C_e}{S_n Q_e}\right) \tag{6.46}$$

where C_e is the total cost of equipment in thousands of dollars (including debugging, etc.), given by Equation 6.43 and Equation 6.44, and W_t is the total personnel rate given by $1.363nW_a + xnTW_{\text{tech}}$.

Substitution of all these values and the equipment costs determined earlier into Equation 6.46 gives the following: for a one-arm system,

$$C_{d1} = 0.622 + 0.022n \tag{6.47}$$

and, for a two-arm system,

$$C_{d2} = 0.647 + 0.016n \tag{6.48}$$

These equations are plotted in Figure 6.16, where it can be seen that the economics of one- and two-arm single-station systems are very similar. Therefore, the decision as to which type of system to use must be made on an individual basis. However, it can be seen that single-station automatic systems used for assemblies containing more than about 18 parts are unlikely to be economical for the conditions assumed. An average station cycle time for such an assembly would be approximately 97 sec for a single-arm system and 59 sec for a two-arm system.

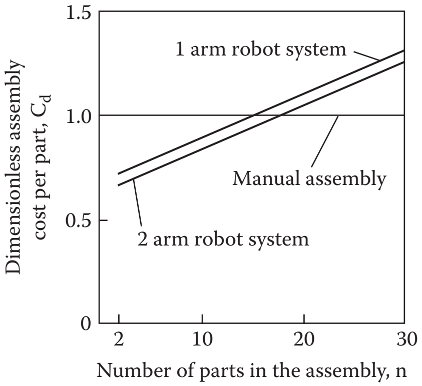


FIGURE 6.16 Effect of number of parts on relative assembly costs for single-station robot systems.

6.5.4 MULTISTATION TRANSFER SYSTEMS

6.5.4.1 Equipment Costs

When the demand for a product is greater than can be assembled on a single-station assembly machine, duplicates of such machines can be installed or, alternatively, a multistation free-transfer machine can be employed. Our typical candidate assembly profile can again be used to study the economics involved in the latter choice.

On a free-transfer machine, it is usually not possible to perform manual operations at any station in which automatic operations are carried out. Similarly, those operations involving special-purpose workheads must be carried out at separate stations. From the information on the profile of the candidate assembly, the number of manual stations will be $0.12n$, and the number of stations with special-purpose workheads will be $0.15n$. The remaining parts ($0.7n$) will be assembled by robots, and the number of stations will depend on the required assembly rate. From Equation 6.33, if the plant efficiency P_e is 80%, the station cycle time (neglecting downtime) would be $5.76/V_s$, where V_s is the annual volume per shift. The figure for the average assembly time per part for a one-arm system used earlier was 5.4 sec, so that the maximum number of parts assembled at one robot station n_r would be given by

$$n_r = \frac{5.76}{5.14V_s} = \frac{1.12}{V_s} \tag{6.49}$$

and the number of robot stations n_t on the machine would then be

$$n_t = \frac{0.7n}{n_r} = 0.625nV_s \tag{6.50}$$

Table 6.3 gives a breakdown of the equipment costs for a multistation free-transfer machine. Summing these equipment costs gives the total cost C_{et} for a free-transfer machine,

$$C_{et} = (12.77 + 78.5V_s)n \tag{6.51}$$

It should be noted that this equation is valid only for assemblies containing at least six parts and with a station cycle time of at least 8.15 sec to allow for a typical manual assembly operation. This latter figure corresponds to an annual production volume per shift V_s of about 0.6 million.

TABLE 6.3
Breakdown of Equipment Costs for a Multistation Free-Transfer Machine to Assemble n Parts at a Rate of V_s Million Assemblies Per Shift

Item	Number Required	Cost per Unit (in Thousands of Dollars)	Total Cost (in Thousands of Dollars)
Robot arm, sensors, controls, etc.	$0.72nV_s$	75	$54nV_s$
Transfer device and 3 work carriers for each workstation	$0.72nV_s$ $+0.27n$	29	$20.9nV_s$ $+7.8n$
Grippers	$0.72nV_s$	5	$3.6nV_s$
Magazines, pallets, etc., for manual loading	$0.22n$	1	$0.22n$
Special-purpose feeders	$0.65n$	5	$3.25n$
Special-purpose workheads	$0.15n$	10	$1.5n$

6.5.4.2 Cost Equation

As with the analysis for single-station machines, it will be assumed that assembly workers are required only for the direct assembly and fault-correction procedures and can be engaged in tasks unrelated to the particular assembly for the remaining time. The downtime on a properly designed free-transfer machine approaches a value twice that for one individual station. Thus, the number of parts n in Equation 6.45 should be regarded as twice the number of parts n assembled at one robot station, which is given by Equation 6.49

For a free-transfer machine, therefore,

$$t_{\mathrm{pr}} = \frac{6.43}{V_s} \tag{6.52}$$

After substitution in Equation 6.46, we get

$$C_{dt} = 0.567 + \frac{0.056}{V_s} \tag{6.53}$$

This result is plotted in Figure 6.17 to show the effects of annual production volume on the cost of assembly. For comparison purposes, the results for single-station robot machines assembling ten parts and for special-purpose machines assembling ten parts are shown on the same figure.

It can be seen that the single-station robot machines and the special-purpose machines are each represented by one point on the graph. If these machines are underutilized, the cost of assembly increases rapidly. If volumes greater than those produced by one machine are needed, further identical machines could be used, giving the same assembly cost. However, with the multistation robot

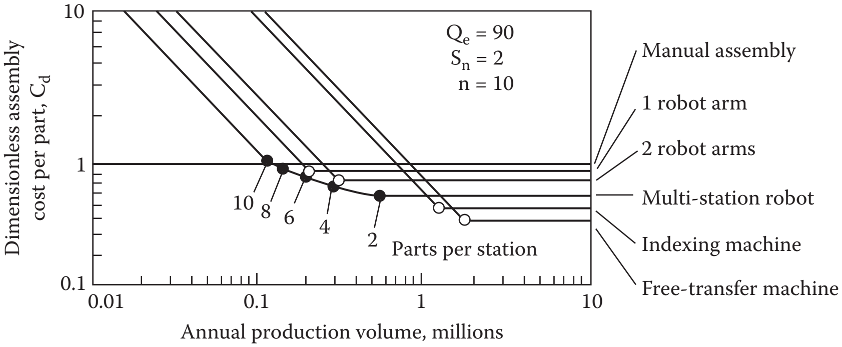


FIGURE 6.17 Effect of annual production volume on relative cost of assembly.

machine, a degree of flexibility is available. By selecting the number of parts assembled at each station, the machine can be designed to match, within limits, the required production volume.

From Figure 6.17, it can be seen that for the conditions represented, special-purpose machines would be recommended for production volumes greater than about 1.5 million/year. For volumes lower than about 200,000, manual bench assembly is preferable. Between these figures, assembly systems using robots might be economical.

REFERENCES

1. Boothroyd, G. and Dewhurst, P., Design for Assembly Software Toolkit, Boothroyd Dewhurst, Wakefield, RI, 1990.
2. Boothroyd, G. and Ho, C., Performance and Economics of Programmable Assembly Systems, Society of Manufacturing Engineers, Technical Paper AD77–720, 1977.
3. Boothroyd, G., Economics of Assembly Systems, *Journal of Manufacturing Systems*, Vol. 1, No. 1, 1982, pp. 111–127.
4. Lynch, P.M., Economic Modeling and Design Criteria for Programmable Assembly Machines, Report T-625, The Charles Stark Draper Laboratory, Cambridge, MA, June 1976.
5. Boothroyd, G., Economics of General-Purpose Assembly Robots, *Annals of the CIRP*, Vol. 33, No. 1, 1984, p. 287.

7 Design for Manual Assembly

7.1 INTRODUCTION

Although there are many ways to increase manufacturing productivity (utilizing improved materials, tools, processes, plant layout, etc.), consideration of manufacturing and assembly during product design holds the greatest potential for significant reduction in production costs and increased productivity. Robert W. Militzer, one-time president of the Society of Manufacturing Engineers. has stated [1]:

> … as manufacturing engineers, we could do far more to improve productivity if we had greater input to the design of the product itself … . It is the product designer who establishes the production [manufacture and assembly] process. For the fact is that much of the production process is implicit in product design.

In other words, if the product is poorly designed for manufacture and assembly, techniques can be applied only to reduce to a minimum the impact of the poor design. Improving the design itself is not worth considering at this late stage; usually, too much time and money have already been expended in justifying the design to consider major changes or even a completely new design. Only when manufacture and assembly techniques are incorporated early in the design stage (i.e., product design for ease of manufacture and assembly) will productivity be significantly affected.

7.2 WHERE DESIGN FOR ASSEMBLY FITS IN THE DESIGN PROCESS

The design process is an iterative, complex, decision-making engineering activity that leads to detailed drawings by which manufacturing can economically produce a quantity of identical products that can be sold. The design process usually starts with the identification of a need, proceeds through a sequence of activities to seek an optimal solution to the problem, and ends with a detailed description of the product.

The three main phases of the design process are the feasibility study, the preliminary design, and the detail design. Before any attempt is made to find possible solutions that may satisfy the hypothetical needs, the design problem is identified and formulated. During the feasibility study, plausible solutions are explored and rough orders-of-magnitude checks are made on performance and perhaps product costs. Performance specifications for the most promising ideas are quantified during the preliminary design, and then the detail design results in the piece-part and assembly drawings that define all the characteristics of the product and its components.

Throughout the design process, the design team may need to factor many variables into their thinking and make numerous trade-offs with respect to performance, cost, reliability, service, and other attributes. Compared to these concerns, manufacturing and assembly costs tend to be difficult for design engineers to quantify and, consequently, do not receive the attention they warrant.

Design for assembly (DFA) should be considered at all stages of the design process. As the design team conceptualizes alternative solutions and begins to realize their thoughts on paper, it should give serious consideration to the ease of assembly of the product or subassembly during production and during field service.

As concepts are analyzed against selected cost and performance criteria, a systematic analysis of product assemblability should be routinely performed. If cost or performance analysis requires that a concept be altered or redefined, then the ease of assembly of the reconceived design should be analyzed before final approval is given. As part of the detail design of parts and assemblies, part features, dimensions, and tolerances should be checked to make certain that they reflect the findings and conclusions of the DFA analysis.

Design engineers need a DFA tool to analyze effectively the ease of assembly of the products or subassemblies they design. The design tool should provide quick results and be simple and easy to use. It should ensure consistency and completeness in its evaluation of product assemblability. It should also eliminate subjective judgment from design assessment, allow free association of ideas, enable easy comparison of alternate designs, ensure that solutions are evaluated logically, identify assembly problem areas, and suggest alternate approaches for improving the manufacturing and assembly of the product.

By applying a DFA tool, communication between manufacturing and design engineering is improved, and ideas, reasoning, and decisions made during the design process become well documented for future reference.

The original DFA analysis method, developed as a result of extensive research, provides methodological procedures for evaluating and improving product design for both economic manufacture and assembly. The DFA analysis method was originally published in the form of a "Design for Assembly Handbook," but has since been refined and expanded and is now available in the form of DFA software [2]. The goal of DFA is achieved by providing manufacturing input at the conceptualization stage of the design process in a logical and organized fashion. Another result of this approach is the availability of a clearly defined procedure for evaluating a design with respect to its ease of manufacture and assembly. In this manner a feedback loop is provided to aid designers in measuring improvements resulting from specific design changes. This procedure also functions as a tool for motivating designers; through this approach, they can evaluate their own designs and, if possible, improve them. In both cases, the design is studied and improved at the conceptual stage and can be simply and inexpensively changed before involving manufacture and assembly. The DFA method attempts to meet these objectives by:

1. Minimizing the dependence of the design engineer on the support of the manufacturing engineer by providing much of the assembly information needed to design new products for "ease of assembly."
2. Guiding the designer to simplify the product so that savings in both assembly costs and piece-parts costs can be realized.
3. Gathering information normally possessed by the experienced design engineer and arranging it, in a convenient way, for use by less experienced designers.
4. Establishing a data base that consists of assembly times and cost factors for various design situations and production conditions.

The analysis of a product design for ease of assembly depends to a large extent on whether the product is to be assembled manually, with special-purpose automation, with general-purpose automation (robots), or with a combination of these. For example, the criteria for ease of automatic feeding and orienting are much more stringent than those for manual handling of parts. The following discussion will introduce design for manual assembly as it is always necessary to use manual assembly costs as a basis for comparison. In addition, even when automation is being seriously considered, some operations may have to be carried out manually, and it is necessary to include the cost of these operations in the analysis.

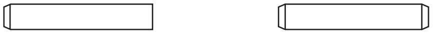
7.3 GENERAL DESIGN GUIDELINES FOR MANUAL ASSEMBLY

As a result of experience in applying DFA, it has been possible to develop general design guidelines that attempt to consolidate manufacturing knowledge and present them to the designer in the form of simple rules to be followed when creating a design. The process of manual assembly can be divided naturally into two separate areas: handling (acquiring, orienting, and moving the parts) and insertion and fastening (mating a part to another part or group of parts). The following design for manual assembly guidelines address each of these areas.

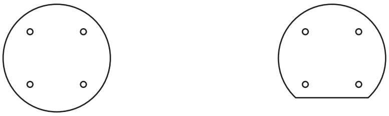
7.3.1 Design Guidelines for Part Handling

In general, for ease of part handling, a designer should attempt to:

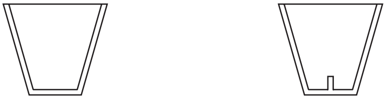
1. Design parts that have end-to-end symmetry and rotational symmetry around the axis of insertion. If this cannot be achieved, try to design parts having the maximum possible symmetry (see Figure 7.1a).



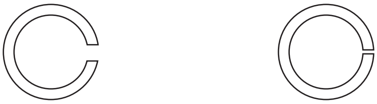
(a) Asymmetrical Symmetrical



(b) Slightly asymmetrical Pronounced asymmetrical



(c) Will jam Cannot jam



(d) Will tangle Cannot tangle

FIGURE 7.1 Geometrical features affecting part handling.

2. Design parts that, in those instances in which the part cannot be made symmetric, are obviously asymmetric (see Figure 7.1b).
3. Provide features that will prevent jamming of parts that tend to nest or stack when stored in bulk (see Figure 7.1c).
4. Avoid features that will allow tangling of parts when stored in bulk (see Figure 7.1d).
5. Avoid parts that stick together or are slippery, delicate, flexible, very small or very large, or that are hazardous to the handler (i.e., parts that are sharp, splinter easily, etc.) (see Figure 7.2).

7.3.2 Design Guidelines for Insertion and Fastening

For ease of insertion, a designer should:

1. Design so that there is little or no resistance to insertion and provide chamfers to guide insertion of two mating parts. Generous clearance should be provided, but care must be taken to avoid clearances that will result in a tendency for parts to jam or hang up during insertion (see Figure 7.3–Figure 7.6).
2. Standardize by using common parts, processes, and methods across all models and even across product lines to permit the use of higher-volume processes that normally result in lower product costs (see Figure 7.7).

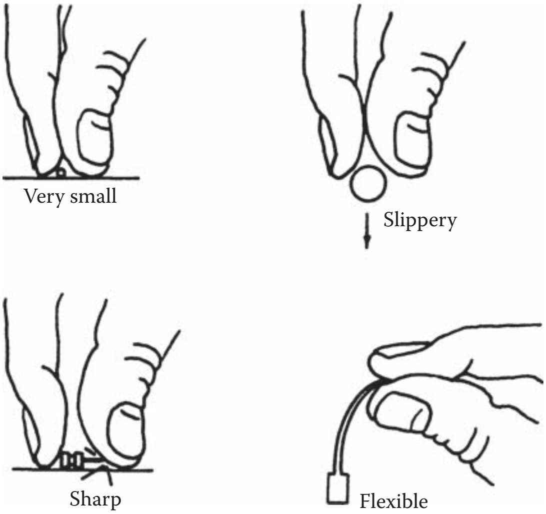
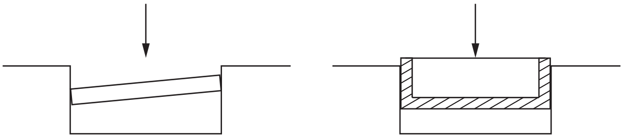


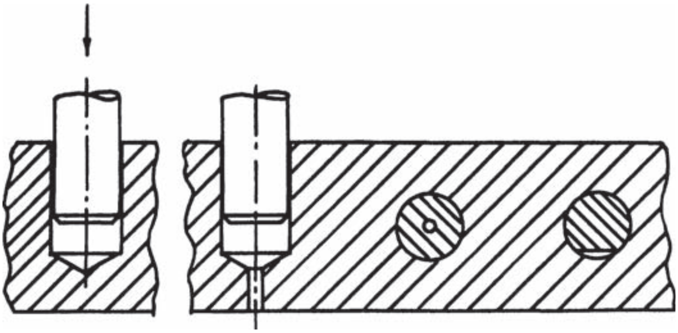
FIGURE 7.2 Some other features affecting part handling.



Part jams across corners

Part cannot jam

FIGURE 7.3 Incorrect geometry can allow part to jam during insertion.



Insertion difficult

Hole in work

Hole in pin

Flat on pin

FIGURE 7.4 Provision of air-relief passages to improve insertion into blind holes.

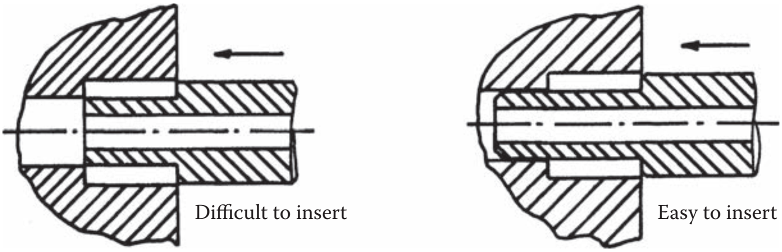


FIGURE 7.5 Design for ease of insertion: assembly of long stepped bushing into counterbored hole.

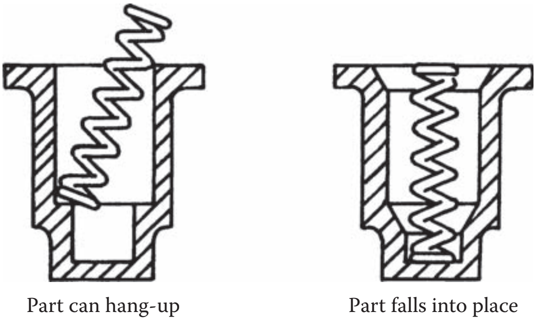


FIGURE 7.6 Provision of chamfers to allow easy insertion.

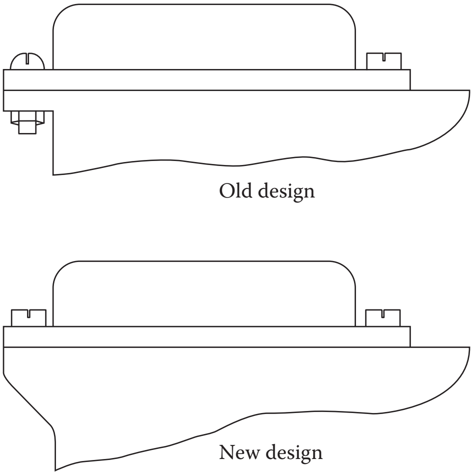


FIGURE 7.7 Standardize parts.

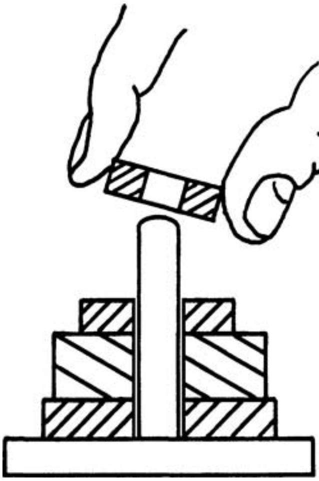


FIGURE 7.8 Single-axis pyramid assembly.

3. Use pyramid assembly — provide for progressive assembly about one axis of reference. In general, it is best to assemble from above (see Figure 7.8).
4. Avoid, where possible, the necessity for holding parts down to maintain their orientation during manipulation of the subassembly or during the placement of another part (see Figure 7.9). If holding down is required, then try to design so that the part is secured as soon as possible after it has been inserted.
5. Design so that a part is located before it is released. A potential source of problems in the placing of a part occurs when, because of design constraints, a part has to be released before it is positively located in the assembly. Under these circumstances, reliance is placed on the trajectory of the part being sufficiently repeatable to consistently locate it (see Figure 7.10).

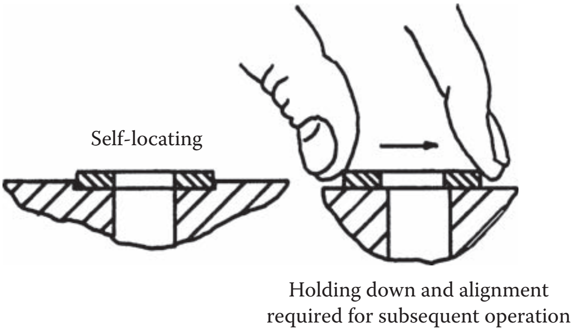
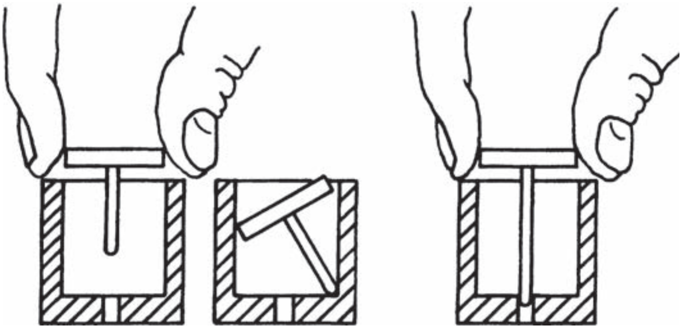

Self-locating
Holding down and alignment required for subsequent operation

FIGURE 7.9 Provision of self-locating features to avoid holding down and alignment.



Part must be released before it is located

Part located before release

FIGURE 7.10 Design to aid insertion.

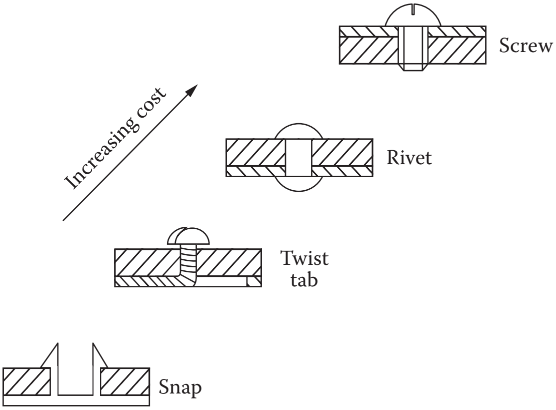


FIGURE 7.11 Common fastening methods.

6. Consider, when common mechanical fasteners are used, the following sequence, which indicates the relative cost of different fastening processes, listed in order of increasing manual assembly cost (Figure 7.11).
7. Avoid the need to reposition the partially completed assembly in the fixture (see Figure 7.12).

Although functioning well as general rules to follow when design for assembly is carried out, guidelines are insufficient in themselves for a number of reasons. First, guidelines provide no means by which to evaluate a design quantitatively for ease of assembly. Second, there is no relative ranking of all the guidelines that can be used by the designer to indicate which guidelines result in the greatest improvements in handling and assembly; there is no way to estimate the improvement resulting from the elimination of a part or from the redesign of

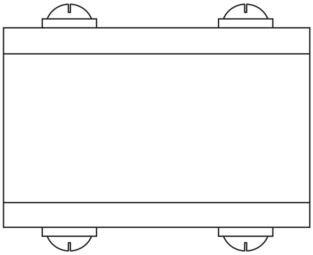


FIGURE 7.12 Insertion from opposite directions requires repositioning of assembly.

a part for handling, etc. It is, then, impossible for the designer to know which guidelines to emphasize during the design of a product.

Finally, these guidelines are simply a set of rules that, when viewed as a whole, provide the designer with suitable background information to be used to develop a design that will be more easily assembled than a design developed without such a background. An approach must therefore be used that provides the designer with an organized method that not only encourages the design of a product that is easy to assemble but also provides an estimate of how much easier it is to assemble one design, with certain handling and assembly features, than to assemble another design with different handling and assembly features. The following describes the approach used in the DFA analysis method that provides the means of quantifying assembly difficulty.

7.4 DEVELOPMENT OF A SYSTEMATIC DFA ANALYSIS METHOD

Starting in 1977, analytical methods were developed [3] for determining the most economical assembly process for a product and for analyzing ease of manual, automatic, and robot assembly. Experimental studies were performed [4–6] to measure the effects of symmetry, size, weight, thickness, and flexibility on manual handling time. Additional experiments were conducted [7] to quantify the effect of part thickness on the grasping and manipulation of a part using tweezers, the effects of spring geometry on the handling time of helical compression springs, and the effect of weight on handling time for parts requiring two hands for grasping and manipulation.

Regarding the design of parts for ease of manual insertion, experimental and theoretical analyses were performed [8–12] on the effect of chamfer design on manual insertion time, the design of parts to avoid jamming during assembly, the effect of part geometry on insertion time, and the effects of obstructed access and restricted vision on assembly operations.

A classification and coding system for manual handling, insertion, and fastening processes, based on the results of these studies, was presented in the form of a time standard system for designers to use in estimating manual assembly times [13,14]. To evaluate the effectiveness of this DFA method, the ease of

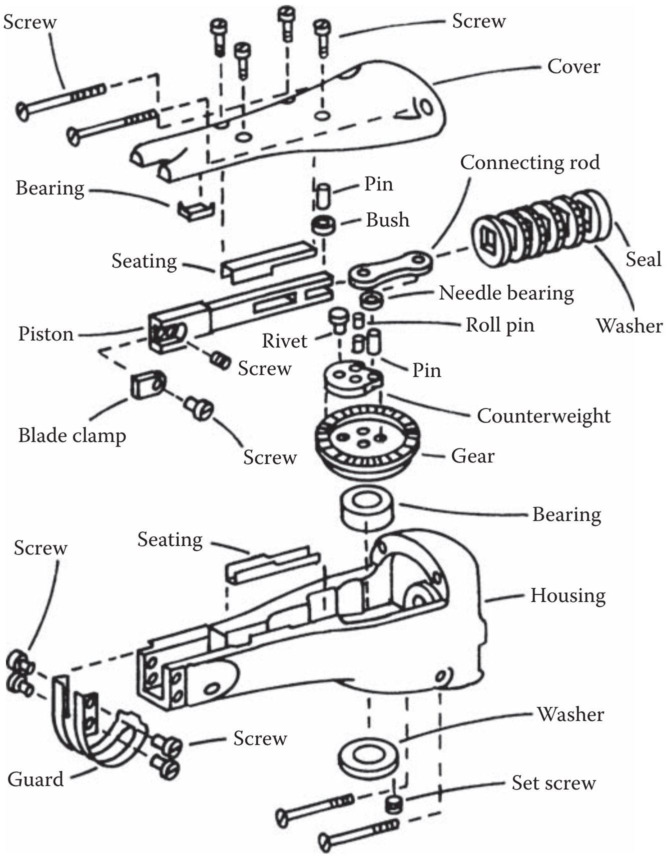


FIGURE 7.13 Power saw (initial design: 41 parts, 6.37 min assembly time). (From Ellison, B. and Boothroyd, G., Applying Design for Assembly Handbook to Reciprocating Power Saw and Impact Wrench, Report #10, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, August 1980. With permission.)

assembly of a two-speed reciprocating power saw and an impact wrench was analyzed, and the products were then redesigned for easier assembly [15]. The initial design of the power saw (Figure 7.13) had 41 parts and an estimated assembly time of 6.37 min. The redesign (Figure 7.14) had 29 parts for a 29% reduction in part count and an estimated assembly time of 2.58 min for a 59% reduction in assembly time. The outcome of further analyses [15] was a more than 50% saving in assembly time, a significant reduction in parts count, and an anticipated improvement in product performance.

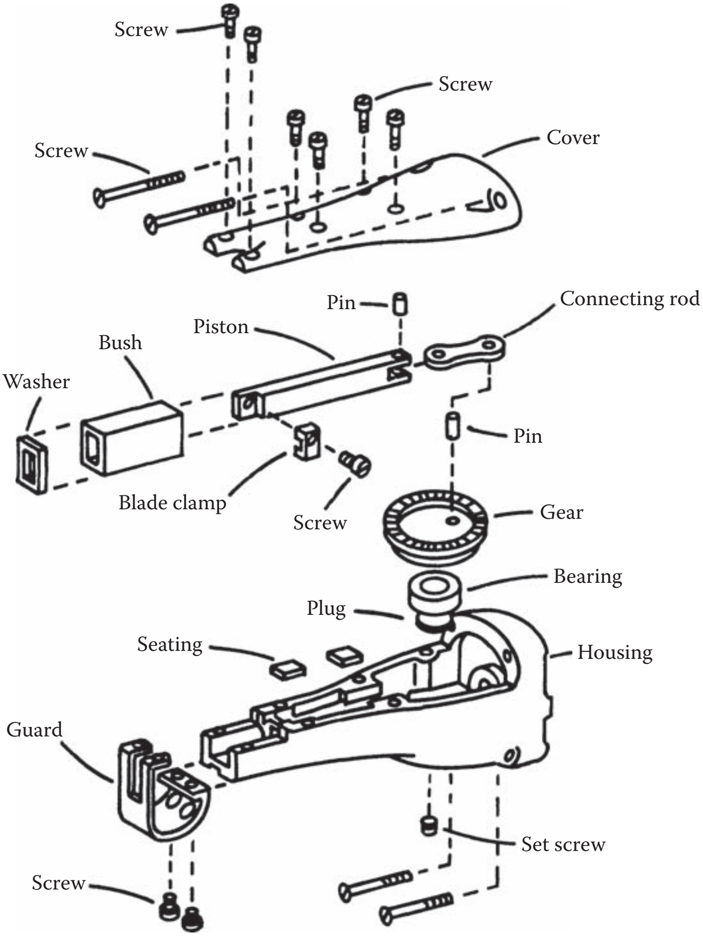


FIGURE 7.14 Power saw (new design: 29 parts, 2.58 min assembly time). (From Ellison, B. and Boothroyd, G., Applying Design for Assembly Handbook to Reciprocating Power Saw and Impact Wrench, Report #10, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, August 1980. With permission.)

7.5 DFA INDEX

An essential ingredient of the DFA method is the use of a measure of the *DFA Index* of a proposed design.

In general, the two main factors that influence the assembly cost of a product or subassembly are: (1) the total number of the parts and (2) the ease of handling, insertion, and fastening of the parts. The term *DFA Index* is used to denote a figure obtained by dividing the theoretical minimum assembly time by the actual assembly time. The equation for calculating the DFA Index E_{ma} is

$$E_{ma} = N_{min}\, t_a / t_{ma} \tag{7.1}$$

where N_{min} is the theoretical minimum number of parts, t_a is the basic assembly time for one part, and t_{ma} is the estimated time to complete the assembly of the actual product. The basic assembly time is the average assembly time for a part that presents no handling, insertion, or fastening difficulties.

The figure for the theoretical minimum number of parts represents an ideal situation in which separate parts are combined into a single part unless, as each part is added to the assembly, one of the following criteria is met:

1. The part moves relative to all other parts already assembled during the normal operating mode of the final product. (Small motions that can be accommodated by elastic hinges do not qualify.)
2. The part must be of a different material than all other parts assembled (for insulation, isolation, vibration damping, etc.)
3. The part must be separate from all other assembled parts; otherwise, the assembly of parts meeting one of the above criteria would be prevented.

It should be pointed out that these criteria are to be applied without taking into account general design requirements. For example, separate fasteners will not generally meet any of the above criteria and should always be considered for elimination. To be more specific, the designer considering the design of an automobile engine may feel that the bolts holding the cylinder head onto the engine block are necessary separate parts. However, they could be eliminated by combining the cylinder head with the block, an approach that is used in some engines.

If applied properly, these criteria require the designer to consider means whereby the product can be simplified, and it is through this process that enormous improvements in manufacturability and savings in product cost are often achieved. However, it is also necessary to be able to quantify the effects of changes in design schemes in terms of assembly time and costs. For this purpose, the DFA method incorporates a system for estimating assembly cost that, together with estimates of part costs, will give the designer the information needed to make appropriate trade-off decisions.

7.6 CLASSIFICATION SYSTEM FOR MANUAL HANDLING

In the DFA method, the classification system for manual handling processes is a systematic arrangement of part features in order of increasing handling difficulty levels. The part features that affect manual handling time significantly are:

Size
Thickness
Weight
Nesting
Tangling
Fragility
Flexibility
Slipperiness
Stickiness
Necessity for using two hands
Necessity for using grasping tools
Necessity for optical magnification
Necessity for mechanical assistance

The original classification system for manual handling processes, along with its associated definitions and corresponding time standards, is presented in Figure 7.15. It can be seen that the classification numbers consist of two digits; each digit is assigned one of 10 numerical symbols (0 to 9). The first digit of the coding system is divided into the following four main groups:

I.	First digit 0–3	Parts of nominal size and weight that are easy to grasp and manipulate with one hand (without the aid of tools)
II.	First digit 4–7	Parts that require grasping tools to handle because of their small size
III.	First digit 8	Parts that severely nest or tangle in bulk
IV.	First digit 9	Parts that require two hands, two persons, or mechanical assistance in handling

Groups I and II are further subdivided into categories representing the amount of orientation required, based on the symmetry of the part.

The second digit of the handling code is based on flexibility, slipperiness, stickiness, fragility, and nesting characteristics of a part. The second digit also depends on the group divisions of the first digit in the following manner:

I.	For a first digit 0–3	The second digit classifies the size and thickness of the part.
II.	For a first digit 4–7	The second digit classifies the part thickness, type of tool required for handling the part, and the necessity for optical magnification during the handling process.
III.	For a first digit 8	The second digit classifies the size and symmetry of a part.
IV.	For a first digit 9	The second digit classifies the symmetry, weight, and interlocking characteristics of parts in bulk.

MANUAL HANDLING–ESTIMATED TIMES (seconds)

Key:

ONE HAND

			Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
			Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
			Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand without the aid of grasping tools	$(\alpha + \beta) < 360^\circ$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	$360^\circ \le (\alpha + \beta) < 540^\circ$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	$540^\circ \le (\alpha + \beta) < 720^\circ$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	$(\alpha + \beta) = 720^\circ$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
				Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
				Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
				Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
				0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	$\alpha \le 180^\circ$	$0 \le \beta \le 180^\circ$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		$\beta = 360^\circ$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	$\alpha = 360^\circ$	$\alpha \le \beta \le 180^\circ$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		$\beta = 360^\circ$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

		Parts present no additional handling difficulties					Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		$\alpha \le 180^\circ$			$\alpha = 360^\circ$		$\alpha \le 180^\circ$			$\alpha = 360^\circ$	
		Size >15 mm	6 mm ≤ size ≤ 15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤ 15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS or assistance required for LARGE SIZE

		Parts can be handled by one person without mechanical assistance									Two persons or mechanical assistance required for parts manipulation
		Parts do not severely nest or tangle and are not flexible								Parts severely nest or tangle or are flexible (2)	
		Part weight <10 lb				Parts are heavy (>10 lb)					
		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)			
		$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$		
		0	1	2	3	4	5	6	7	8	9
Two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

FIGURE 7.15 Original classification system for part features affecting manual handling time (© Boothroyd Dewhurst, Inc., reproduced with permission).

FIGURE 7.15 (CONTINUED)

Notes:

1. Parts can present handling difficulties if they nest or tangle, stick together because of magnetic force or grease coating, etc., are slippery, or require careful handling. Parts that nest or tangle are those that interlock when in bulk but can be separated by one simple manipulation of a single part; for example, taper cups, closed-end helical springs, circlips, etc. Parts that are slippery are those that easily slip from fingers or standard grasping tool because of their shape and/or surface condition. Parts that require careful handling are those that are fragile or delicate, have sharp corners or edges, or present other hazards to the operator.
2. Parts that nest or tangle severely are those parts that interlock when in bulk and both hands are needed to apply a separation force or achieve specific orientation of interlocking parts to achieve separation. Flexible parts are those that substantially deform during manipulation and necessitate the use of two hands. Examples of such parts are large paper or felt gaskets, rubber bands or belts, etc.

7.7 CLASSIFICATION SYSTEM FOR MANUAL INSERTION AND FASTENING

The DFA classification system for manual insertion and fastening processes is concerned with the interaction between mating parts as they contact and go together. Manual insertion and fastening consists of a finite variety of basic assembly tasks (peg-in-hole, screw, weld, rivet, force-fit, etc.) that are common to most manufactured products. The design features that significantly affect manual insertion and fastening times are:

Accessibility of assembly location
Ease of operation of assembly tool
Visibility of assembly location
Ease of alignment and positioning during assembly
Depth of insertion

The corresponding classification system and its associated definitions and time standards are presented in Figure 7.16.

There were 100 code numbers in the original manual insertion and fastening coding system, as in the manual handling coding system. However, it was subsequently found that certain categories of codes were not necessary in practice and were omitted in the later versions of the method. The two-digit code numbers range from 00 to 99. The first digit is divided into three main groups:

I.	First digit 0–2	Part is not secured immediately after insertion.
II.	First digit 3–5	Part secures itself or another part immediately after insertion.
III.	First digit 9	Process involves parts that are already in place.

MANUAL INSERTION–ESTIMATED TIMES (seconds)

Key:

PART ADDED but NOT SECURED

			Alter assembly no holding down required to maintain orientation and location (3)				Holding down required during subsequent processes to maintain orientation at location (3)			
			Easy to align and position during assembly (4)		Not easy to align or position during assembly		Easy to align and position during assembly (4)		Not easy to align or position during assembly	
			No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)
			0	1	2	3	6	7	8	9
Addition of any part (1) where neither the part itself nor any other part is finally secured immediately	Part and associated tool (including hands) can easily reach the desired location		1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	Part and associated tool (including hands) cannot easily reach the desired location	Due to obstructed access or restricted vision (2)	4	5	5	6	8	9	9	10
		Due to obstructed access and restricted vision (2)	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

Row codes: 0, 1, 2 (in order of the rows above).

PART SECURED IMMEDIATELY

			No screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		Plastic deformation immediately after insertion						Screw tightening immediately after insertion	
					Plastic bending or torsion			Rivetting or similar operation				
						Not easy to align or position during assembly			Not easy to align or position during assembly			
			Easy to align and position with no resistance to insertion (4)	Not easy to align or position during assembly and/or resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position with no torsional resistance (4)	Not easy to align or position and/or torsional resistance (5)
			0	1	2	3	4	5	6	7	8	9
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately	Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
	Part and associated tool (including hands) cannot easily reach desired locaton or tool cannot be operated easily — Due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
	Part and associated tool (including hands) cannot easily reach desired locaton or tool cannot be operated easily — Due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

SEPARATE OPERATION

		Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-fastening processes	
		None or localized plastic deformatiion				Metallurgical processes					
							Additional material required				
		Bending or similar process	Rivetting or similar processes	Screw tightening or other processes	Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	No additional material required (e.g. resistance, friction welding etc.)	Soldering processes	Weld/braze processeses	Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of parts(s), etc.)	Other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
Assembly processes where all solid parts are in place	9	4	7	5	12	7	8	12	12	9	12

FIGURE 7.16 Original classification system for part features affecting insertion and fastening (© Boothroyd Dewhurst, Inc., reproduced with permission).

FIGURE 7.16 (CONTINUED)

Notes:

1. A part is the solid or nonsolid element of an assembly during an assembly process. A subassembly is considered a part if it is added during assembly. However, adhesives, fluxes, fillers, etc., used for joining parts are not considered to be parts.
2. *Obstructed access* means that the space available for the assembly operation causes a significant increase in the assembly time. *Restricted vision* means that the operator has to rely mainly on tactile sensing during the assembly process.
3. *Holding down required* means that the part is unstable after placement or insertion or during subsequent operations and will require gripping, realignment, or holding down before it is finally secured. *Holding down* refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to, or during the next assembly operation. A part is located if it will not require holding down or realignment for subsequent operations and is only partially secured.
4. A part is easy to align and position if the position of the part is established by locating features on the part or on its mating part and insertion is facilitated by well designed chamfers or similar features.
5. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For example, a *press fit* is an interference fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

Groups I and II are further subdivided into classes that consider the effect of obstructed access and/or restricted vision on assembly time.

The second digit of the assembly code is based on the following group divisions of the first digit:

I. For a first digit 0–2 The second digit classifies the ease of engagement of parts and whether holding down is required to maintain orientation or location.

II. For a first digit 3-5 The second digit classifies the ease of engagement of parts and whether the fastening operation involves a simple snap fit, screwing operation, or plastic deformation process.

III. For a first digit 9 The second digit classified mechanical, metallurgical, and chemical processes

It can be seen in Figure 7.15 and Figure 7.16 that, for each two-digit code number, average handling or insertion and fastening times are given. Thus, we have a set of time standards that can be used to estimate manual assembly times. These time standards were obtained from numerous experiments, some of which will now be described.

7.8 EFFECT OF PART SYMMETRY ON HANDLING TIME

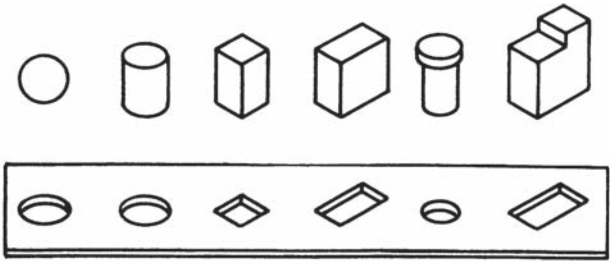
One of the principal geometrical design features that affect the times required to grasp and orient a part is its symmetry. Assembly operations always involve at least two component parts: the part to be inserted and the part or assembly (receptacle) into which the part is inserted [16]. Orientation involves the proper alignment of the part to be inserted relative to the corresponding receptacle and can always be divided into two distinct operations: (1) alignment (rotation) of the axis of the part that corresponds to the axis of insertion, and (2) rotation of the part about this axis.

It is therefore convenient to define two kinds of symmetry for a part:

1. Alpha symmetry, which depends on the angle through which a part must be rotated about an axis perpendicular to the axis of insertion
2. Beta symmetry, which depends on the angle through which a part must be rotated about the axis of insertion.

For example, a long square prism that is to be inserted into a square hole would first have to be rotated about an axis perpendicular to the insertion axis, and as, with such a rotation, the maximum angle for orienting the prism is 180°, this can be termed 180° alpha symmetry. The square prism would then have to be rotated about the axis of insertion, and because the orientation of the prism about this axis would repeat every 90°, this implies 90° beta symmetry. However, if the square prism were to be inserted in a circular hole, it would have 180° alpha symmetry and 0° beta symmetry. Figure 7.17 gives examples of the symmetry of simple-shaped parts.

A variety of predetermined time standard systems are currently used to establish assembly times in industry. In the development of these systems, several different approaches have been employed to determine relationships between the



α	0	180	180	90	360	360
β	0	0	90	180	0	360

FIGURE 7.17 Alpha and beta rotational symmetries for various parts.

amount of rotation required to orient a part and the time required to perform that rotation. The two most commonly used systems are the methods time measurement (MTM) and work factor (WF) systems.

In the MTM system, the "maximum possible orientation" is employed, which is one-half the beta rotational symmetry of a part defined above [17]. The effect of alpha symmetry is not considered in this system. For practical purposes, the MTM system classifies the maximum possible orientation into three groups, namely: (1) symmetric, (2) semisymmetric, and (3) nonsymmetric [4]. Again, these terms refer only to the beta symmetry of a part.

In the WF system, the symmetry of a part is classified by the ratio of the number of ways the part can be inserted to the number of ways the part can be grasped preparatory to insertion [18]. In the example of a square prism to be inserted into a square hole, one particular end first, it can be inserted in four ways out of the eight ways it could be suitably grasped. Hence, on the average, half of the parts grasped require orientation, and this is defined in the WF system as a situation requiring 50% orientation [18]. Thus, in this system, account is taken of alpha symmetry, and some account is taken of beta symmetry. Unfortunately, these effects are combined in such a way that the classification can be applied to only a limited range of part shapes.

Numerous attempts were made to find a single parameter that would give a satisfactory relation between the symmetry of a part and the time required for orientation. It was found that the simplest and most useful parameter was the sum of the alpha and beta symmetries [6]. This parameter, which will be termed the *total angle of symmetry*, is therefore given by

$$\text{Total angle of symmetry} = \alpha + \beta \tag{7.2}$$

The effect of the total angle of symmetry on the time required to handle (grasp, move, orient, and place) a part is shown in Figure 7.18. In addition, the shaded areas indicate the values of the total angle of symmetry that cannot exist. It is evident from these results that the symmetry of a part can be conveniently classified into five groups. However, the first group, which represents a sphere, is not generally of practical interest and, therefore, four groups are suggested that are employed in the coding system for part handling (Figure 7.15).

Comparison of these experimental results with the MTM and WF orientation parameters showed that these parameters do not account properly for the symmetry of a part [6].

7.9 EFFECT OF PART THICKNESS AND SIZE ON HANDLING TIME

Two other major factors that affect the time required for handling during manual assembly are the thickness and the size of the part.

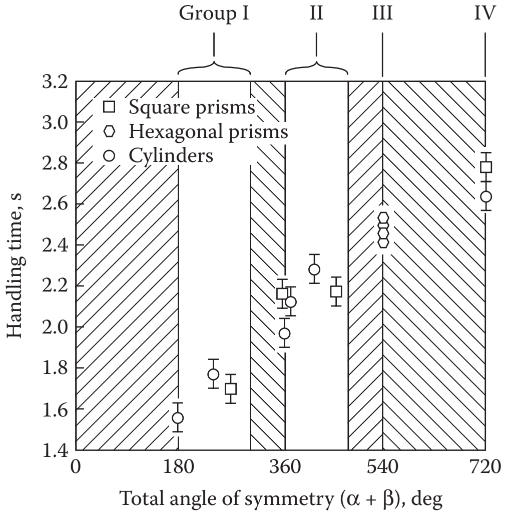


FIGURE 7.18 Effect of symmetry on the time required to handle a part (times are average for two individuals; shaded areas represent nonexistent values of the total angle of symmetry).

The thickness and size of a part are defined in a convenient way in the WF system, and these definitions have been adopted for the DFA method. The thickness of a "cylindrical" part is its radius, whereas, for noncylindrical parts, the thickness is defined as the maximum height of the part with its smallest dimension extending from a flat surface (Figure 7.19). Cylindrical parts are defined as parts having cylindrical or other regular cross sections with five or more sides. When the diameter of such a part is greater than or equal to its length, the part is treated as noncylindrical. The reason for this distinction between cylindrical and noncylindrical parts in defining thickness is illustrated by the experimental curves shown in Figure 7.19. It can be seen that parts with a "thickness" greater than 2 mm present no grasping or handling problems. However, for long cylindrical parts, this critical value would have occurred at a value of 4 mm if the diameter had been used for the "thickness." Intuitively, we know that grasping a long cylinder of 4mm diameter is equivalent to grasping a rectangular part 2 mm thick if each is placed on a flat surface.

The size (also called the *major dimension*) of a part is defined as the largest nondiagonal dimension of the part's outline when projected on a flat surface. It is normally the length of the part. The effects of part size on handling time are shown in Figure 7.20. Parts can be divided into four size categories as illustrated. Large parts involve little or no variation in handling time with changes in their size; the handling time for medium and small parts displays progressively greater sensitivity with respect to part size. Because the time penalty involved in handling very small parts is large and very sensitive to decreasing part size, tweezers are usually required to manipulate such parts.

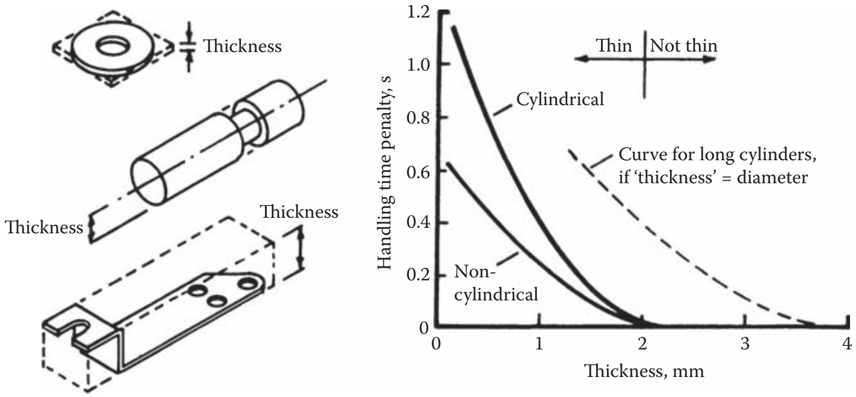


FIGURE 7.19 Effect of part thickness on handling time.

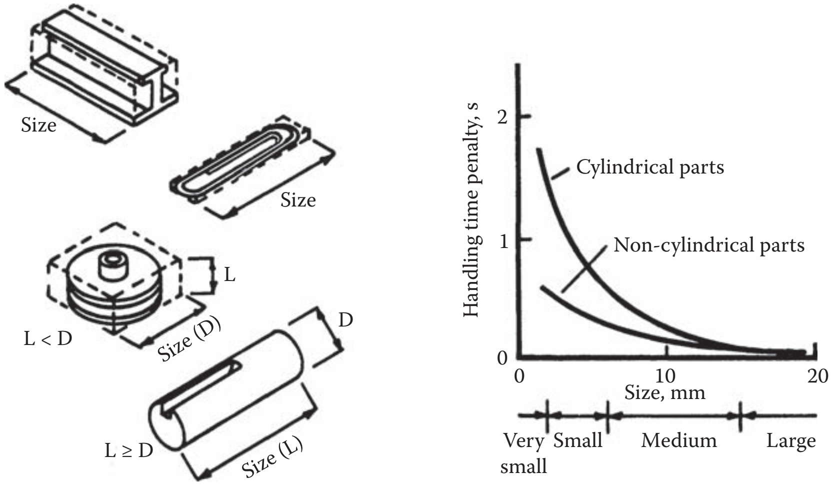


FIGURE 7.20 Effect of part size on handling time.

7.10 EFFECT OF WEIGHT ON HANDLING TIME

Work has been carried out [19] on the effects of weight on the grasping, controlling, and moving of parts. The effect on grasping and controlling is found to be a time addition to the basic time for grasping and controlling, and the effect on moving is found to be a proportional increase. For the effect of weight on a part handled using one hand, the total adjustment t_{pw} to handling time can be represented by the following equation [4]:

$$t_{pw} = 0.0125W + 0.011W\,t_h \tag{7.3}$$

where W(lb) is the weight of the part and t_h (sec) is the basic time for handling a "light" part when no orientation is needed and when it is to be moved a short distance.

An average value for t_h is 1.13 and, therefore, the total time penalty due to weight would be approximately $0.025W$.

If we assume that the maximum weight of a part to be handled using one hand is approximately 10–20 lb, the maximum penalty for weight is 0.25–0.5 sec and is a fairly small correction. Of course, this analysis does not take into account that larger parts will usually be moved greater distances, resulting in more significant time penalties.

7.11 PARTS REQUIRING TWO HANDS FOR MANIPULATION

Parts may require two hands for manipulation when:

1. The part is heavy.
2. Very precise or careful handling is required.
3. The part is large or flexible.
4. The part does not possess holding features, thus making one-hand grasp difficult.

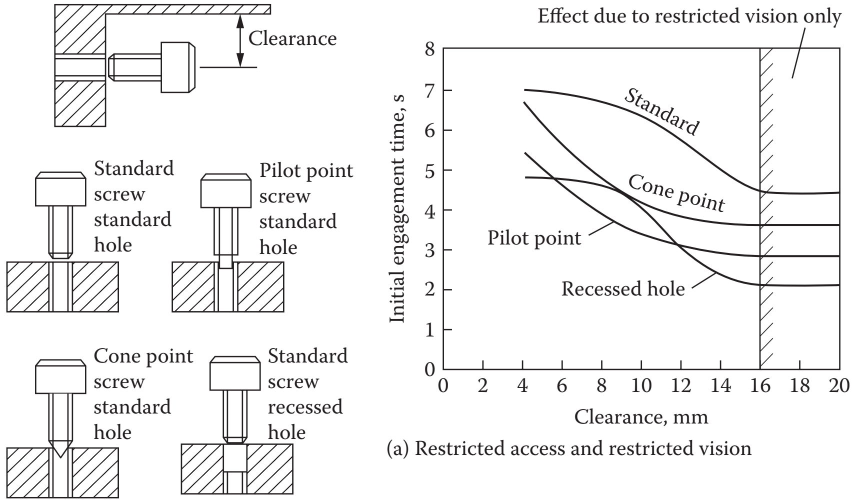
Under these circumstances, a penalty is incurred because the second hand could be engaged in another operation, perhaps grasping another part. Experience shows that a penalty factor of 1.5 should be applied in these cases.

7.12 EFFECTS OF COMBINATIONS OF FACTORS

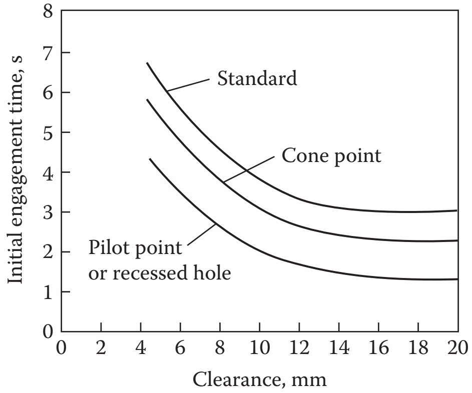
In the previous sections, various factors that affect manual handling times have been considered. However, it is important to realize that the penalties associated with each individual factor are not necessarily additive. For example, if a part requires additional time to move it from A to B, it can probably be oriented during the move. Therefore, it may be wrong to add the extra time for part size and an extra time for orientation to the basic handling time.

7.13 THREADED FASTENERS

Considerable experimental work has been conducted on the time taken to insert threaded fasteners of different types and under a variety of conditions. First, let us consider the time taken to insert a machine screw and engage the threads. Figure 7.21a shows the effects of the shape of the screw point and hole entrance when the assembly worker cannot see the operation and when various levels of obstruction are present. When the distance from the obstructing surface to the hole center was greater than 16 mm, the obstructing surface had no effect on the



(a) Restricted access and restricted vision



(b) Restricted access only

Figure 7.21 Effects of (a) restricted access and restricted vision and (b) restricted access only on initial engagement of screws.

manipulations, and the restriction of vision was the only factor. Under these circumstances, the standard screw inserted into a recessed hole gave the shortest time. For a standard screw with a standard hole, an additional 2.5 sec was required. When the hole was closer to the wall, thereby inhibiting the manipulations, a further time of 2–3 sec was necessary.

Figure 7.21b shows the results obtained under similar conditions but with the worker's vision unrestricted. Comparison with the previous results indicates that restriction of vision had little effect when access was obstructed. This was because the proximity of the obstructing surface allowed tactile sensing to take the place of sight. When the obstruction was removed, however, restricted vision could account for up to 1.5 sec additional time.

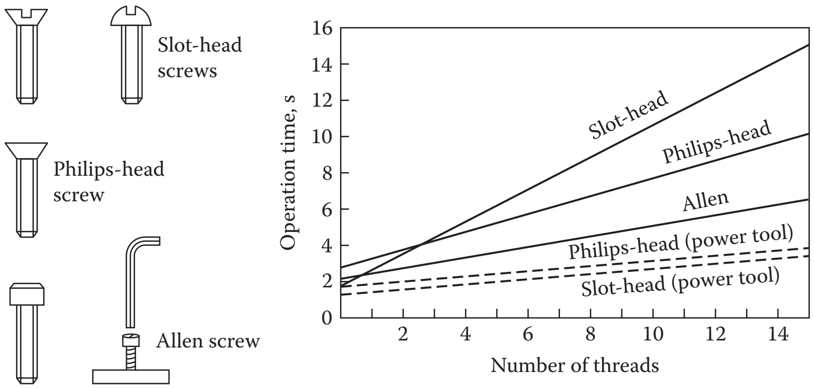


FIGURE 7.22 Effect of number of threads on time to pick up the tool, engage the screw, tighten the screw, and replace the tool.

Once the screw threads are engaged, the assembly worker must grasp the necessary tool, engage it with the screw, and perform sufficient rotations to tighten the screw. Figure 7.22 shows the total time for these operations for a variety of screw head designs and for both hand-operated and power tools. There was no restriction on tool operation for any of these situations. Finally, Figure 7.23 shows the time to turn down a nut using a variety of hand-operated tools, where the operation of the tools was obstructed to various degrees. It can be seen that the penalties for a box-end wrench are as high as 4 sec per revolution when obstructions are present. However, when planning the design of a new product, the designer does not normally consider the type of tool used and can reasonably expect that the best tool for the job will be selected. In the present case, this is either the nut driver or the socket ratchet wrench.

7.14 EFFECTS OF HOLDING DOWN

Holding down is required when parts are unstable after insertion or during subsequent operations. It is defined as a process that, if necessary, maintains the position and orientation of parts already in place prior to, or during, subsequent operations.

7.15 PROBLEMS WITH MANUAL ASSEMBLY TIME STANDARDS

The above sections have presented a small selection of the results of some of the analyses and experiments conducted during the early phases of development of the design for assembly method.

For the development of the classification schemes and time standards presented earlier, it was necessary to obtain an estimate of the average time, in seconds, to complete the operation for all the parts falling within each classification or category.

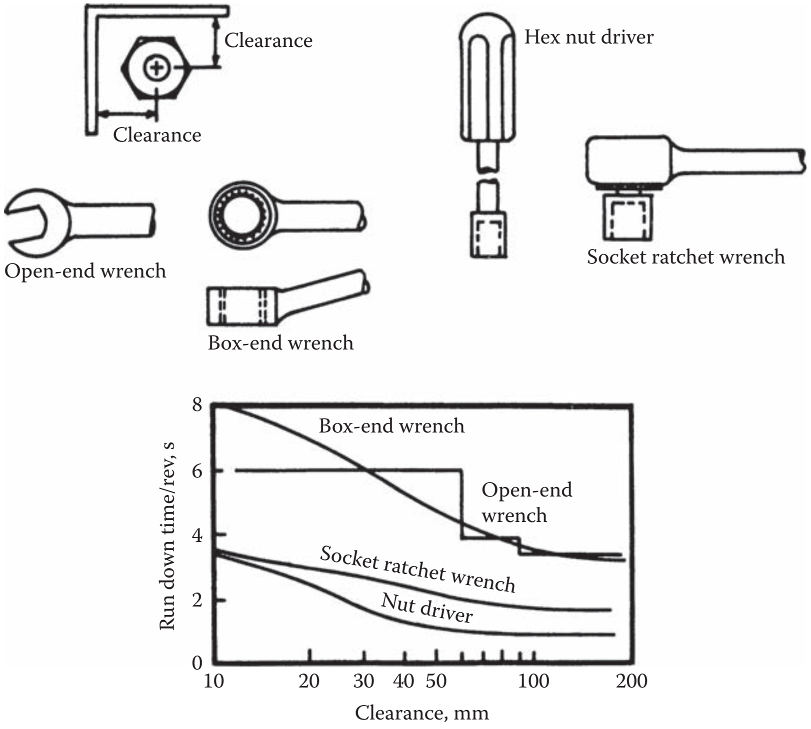


FIGURE 7.23 Effect of obstructed access on time to tighten a nut.

For example, the top item in the left-hand column in Figure 7.15 (code 00) gives a figure of 1.13 sec for the average time to grasp, orient, and move a part that

1. Can be grasped and manipulated with one hand
2. Has a total symmetry angle of less than 360° (a plain cylinder, for example)
3. Is larger than 15 mm
4. Has a thickness greater than 2 mm (or in the case of a long cylinder a diameter greater than 4 mm)
5. Has no handling difficulties, such as flexibility, tendency to tangle or nest, etc.

Clearly, a wide range of parts will fall within this category, and their handling times will vary somewhat. The figure presented is only an average figure for the range of parts.

To illustrate the type of problem that can arise through the use of the group technology coding or classification scheme employed in the DFA method we can consider the assembly of a part having a thickness of 1.9 mm. We shall assume that, except for its thickness of less than 2 mm, the part would be classified as code 00 (Figure 7.15). However, because of the thickness of the part, the appropriate code would be 03, and the estimated handling time would be 1.69 sec instead of 1.13 sec, which represents a time penalty of 0.56 sec. Turning now to the results of experiments for the effect of thickness (Figure 7.19), we can see that, for a cylindrical part, the actual time penalty is on the order of only 0.01–0.02 sec. We would therefore expect an error in our results of about 50%.

Experience has shown that, under normal circumstances, these errors tend to cancel; with some parts, the error results in an overestimate of time and, with some, an underestimate. However, if an assembly contains a large number of identical parts, care must be taken to check whether the part characteristics fall close to the limits of the classification. If they do, then the detailed results presented above should be consulted.

7.16 APPLICATION OF THE DFA METHOD

To illustrate how DFA is applied in practice, we shall consider the controller assembly shown in Figure 7.24. The assembly of this product first involves securing a series of assemblies to the metal frame using screws, connecting these assemblies together in various ways, and then securing the resulting assembly into the plastic cover, again using screws. An undesirable feature of the design of the plastic cover is that the small subassemblies must be fastened to the metal frame before the metal frame can be secured to the plastic cover.

Figure 7.25 shows a completed worksheet analysis for the controller in the form of a tabulated list of operations and the corresponding assembly times and costs. Each assembly operation is divided into handling and insertion, and the corresponding times and two-digit code numbers for each process are given. Assembly starts by placing the pressure regulator (a purchased item) into a fixture. The metal frame is placed onto the projecting spindle of the pressure regulator and secured with the nut. The resulting assembly is then turned over in the fixture to allow for the addition of other items to the metal frame.

Next, the sensor and the strap are placed and held in position while two screws are installed. Clearly, the holding of these two parts and the difficulty of the screw insertions will impose time penalties on the assembly process.

After applying tape to the thread on the sensor, the adapter nut can be screwed into place. Then, one end of the tube assembly is screwed to the threaded extension on the pressure regulator and the other end to the adapter nut. Clearly, both of these are difficult and time-consuming operations.

The PCB assembly is now positioned and held in place while two screws are installed, after which its connector is snapped into the sensor and the earth lead is snapped into place.

The whole assembly must be turned over once again to allow for the positioning and holding of the knob assembly while the screw fastening operation can be carried out. Finally, the plastic cover is placed in position and the entire

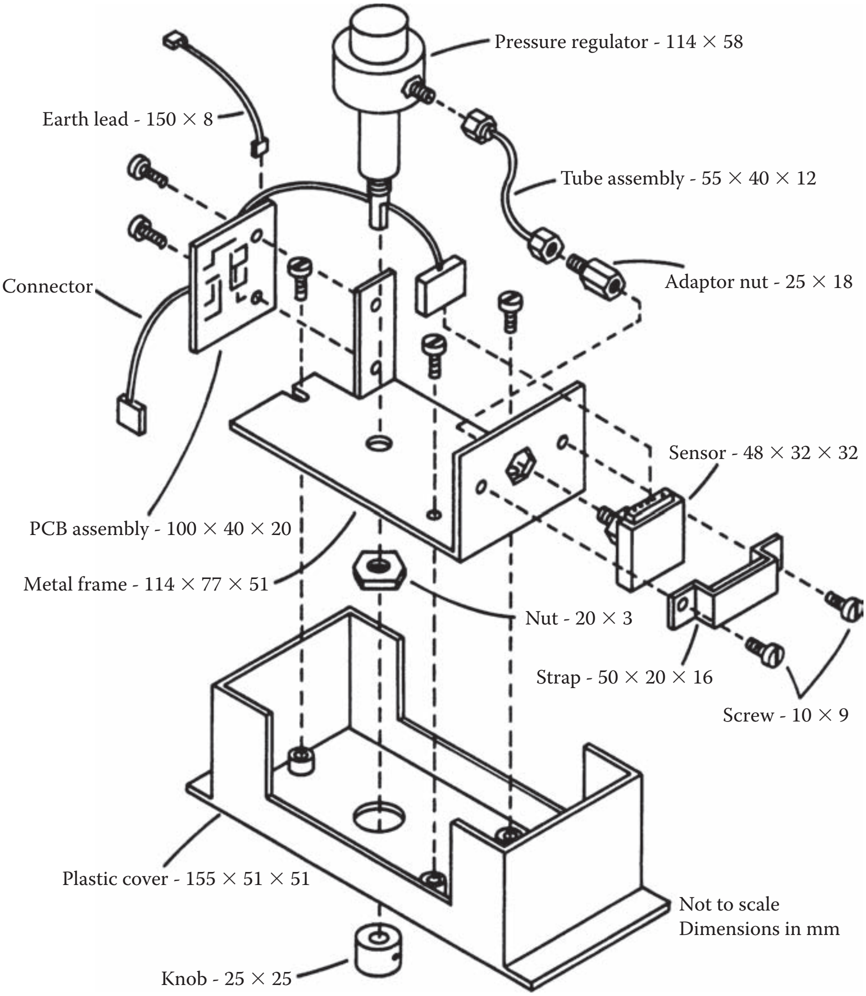


FIGURE 7.24 Controller assembly.

assembly turned over for the third time to allow the three screws to be inserted. It should be noted that access for the insertion of these screws is very restricted.

It is clear from this description of the assembly sequence that many aspects of the design could be improved. However, a step-by-step analysis of each operation is necessary before changes to simplify the product structure and reduce assembly difficulties can be identified and quantified. First, we shall look at how the handling and insertion times are established. The addition of the strap to the metal frame will be considered by way of example. This operation is item 6 on the worksheet, and the line of information is completed as follows:

Item name	Number of items	Manual handling code	Handling time per item, s	Manual insertion code	Insertion time per item, s	Total operation time, s	Figures for min. parts	Description
1. Pressure regulator	1	30	1.95	00	1.50	3.45	1	Place in fixture
2. Metal frame	1	30	1.95	06	5.50	7.45	1	Add
3. Nut	1	00	1.13	39	8.00	9.13	0	Add and screw fasten
4. Reorientation	1			98	9.00	9.00		Reorient and adjust
5. Sensor	1	30	1.95	08	6.50	8.45	1	Add
6. Strap	1	20	1.80	08	6.50	8.30	0	Add and hold down
7. Screw	2	11	1.80	39	8.00	19.60	0	Add and screw fasten
8. Apply tape	1			99	12.00	12.00		Operation
9. Adapter nut	1	10	1.50	49	10.50	12.00	0	Add and screw fasten
10. Tube assembly	1	91	3.00	10	4.00	7.00	0	Add and screw fasten
11. Screw fastening	1			92	5.00	5.00		Operation
12. PCB assembly	1	83	5.60	08	6.50	12.10	1	Add and hold down
13. Screw	2	11	1.80	39	8.00	19.60	0	Add and screw fasten
14. Connector	1	30	1.95	31	5.00	6.95	0	Add and snap fit
15. Earth lead	1	83	5.60	31	5.00	10.60	0	Add and snap fit
16. Reorientation	1			98	9.00	9.00		Reorient and adjust
17. Knob assembly	1	30	1.95	08	6.50	8.45	1	Add and screw fasten
18. Screw fastening	1			92	5.00	5.00		Operation
19. Plastic cover	1	30	1.95	08	6.50	8.45	0	Add and hold down
20. Reorientation	1			98	9.00	9.00		Reorient and adjust
21. Screw	3	11	1.80	49	10.50	36.90	0	Add and screw fasten
Totals	**25**					**227.43**	**5**	

FIGURE 7.25 Completed worksheet analysis for the controller assembly.

Number of items: There is one strap.

Handling code: The insertion axis for the strap is horizontal in Figure 7.24, and the strap can be inserted only one way along this axis so that the alpha angle of symmetry is 360°. If the strap is rotated about the axis of insertion, it will repeat is orientation every 180°, which is, therefore, the beta angle of symmetry. Thus, the total angle of symmetry is 540°. Referring to Figure 7.15, as the strap can be grasped and manipulated using one hand without the aid of tools and because alpha plus beta is 540°, the first digit of the handling code is 2. The strap presents no handling difficulties (can be grasped and separated from bulk easily), its thickness is greater than 2 mm, and its size is greater than 15 mm; therefore, the second digit is 0, giving a handling code of 20.

Handling time: A handling time of 1.8 sec corresponds to a handling code of 20 (Figure 7.15).

Insertion code: The strap is not secured as part of the insertion process, and as there is no restriction to access or vision, the first digit of the insertion code is 0 (Figure 7.16). Holding down is necessary while subsequent operations are carried out, and the strap is not easy to align because no features are provided to facilitate alignment of the screw holes. There will be no resistance to insertion and, therefore, the second digit will be 8, giving an insertion code of 08.

Insertion time: An insertion time of 6.5 sec corresponds to an insertion code of 08 (Figure 7.16).

Total operation time: This is the sum of handling and insertion times multiplied by the number of items. The total operation time for the strap is therefore 8.3 sec.

Figures for minimum parts: As explained earlier, the establishment of a theoretical minimum part count is the most powerful way to identify possible simplifications in the product structure. For the strap, the three criteria for separate parts are applied assuming the pressure regulator, the metal frame, the nut, and the sensor have been assembled:

1. The strap does not move relative to these parts, and so it could theoretically be combined with any of them.
2. The strap does not have to be of a different material — in fact, it could be of the same plastic material as the body of the sensor and, therefore, take the form of two lugs with holes projecting from the body. At this point in the analysis, the designer would probably determine that, because the sensor is a purchased stock item, its design could not be changed. However, it is important to ignore these economic considerations at this stage and consider only theoretical possibilities.
3. The strap clearly does not have to be separate from the sensor in order to allow assembly of the sensor and, therefore, none of the three criteria are met, and the strap becomes a candidate for elimination. For the strap, a zero is placed in the column for minimum parts.

7.16.1 RESULTS OF THE ANALYSIS

Once the analysis is complete for all operations, the appropriate columns can be summed. Thus, for the controller, the total number of parts and subassemblies is 19, and there are 6 additional operations. The total assembly time is 227.43 sec, for a burdened assembly rate of 0.83 cents/sec, the corresponding assembly cost is \$1.89, and the theoretical minimum number of items is 5.

A DFA index is now obtained using Equation 7.1. In this equation, t_a is the basic assembly (handling and insertion) time for one part and can be taken as 3 sec on average. Thus,

$$E_{ma} = N_{min}\, t_a / t_{ma} = 5 \times 3 \;/\; 227.43 = 0.0659 \text{ or approximately } 7\%$$

The high cost assembly processes should now be identified, especially those associated with the installation of parts that do not meet any of the criteria for separate parts. From the worksheet results (Figure 7.25), it can be seen that attention should clearly be paid to combining the plastic cover with the metal frame. This would eliminate the assembly operation for the cover, the three screws, and the reorientation operation, representing a total time saving of 54.35 sec, which constitutes almost 24% of the total assembly time. Of course, the designer must check that the cost of the combined plastic cover and frame is less than the total cost of the individual items.

A summary of the items that can be identified for elimination or combination and the appropriate assembly time savings are presented in Table 7.1.

TABLE 7.1
Possible Design Changes for the Controller

	Design Change	Items	Time Saving (in sec)
1.	Combine plastic cover with frame and eliminate 3 screws and reorientation	19,20,21	54.35
2.	Eliminate strap and 2 screws (snaps in plastic frame to hold sensor if necessary)	6,7	27.9
3.	Eliminate screws holding PCB assembly (provide snaps in plastic frame)	13	19.6
4.	Eliminate 2 reorientations	4,16	18.0
5.	Eliminate tube assembly and screw fastening operation (screw adapter nut and sensor direct to pressure regulator)	10,11	12.0
6.	Eliminate earth lead (not necessary with plastic frame)	15	10.6
7.	Eliminate connector (plug sensor into PCB)	14	6.95

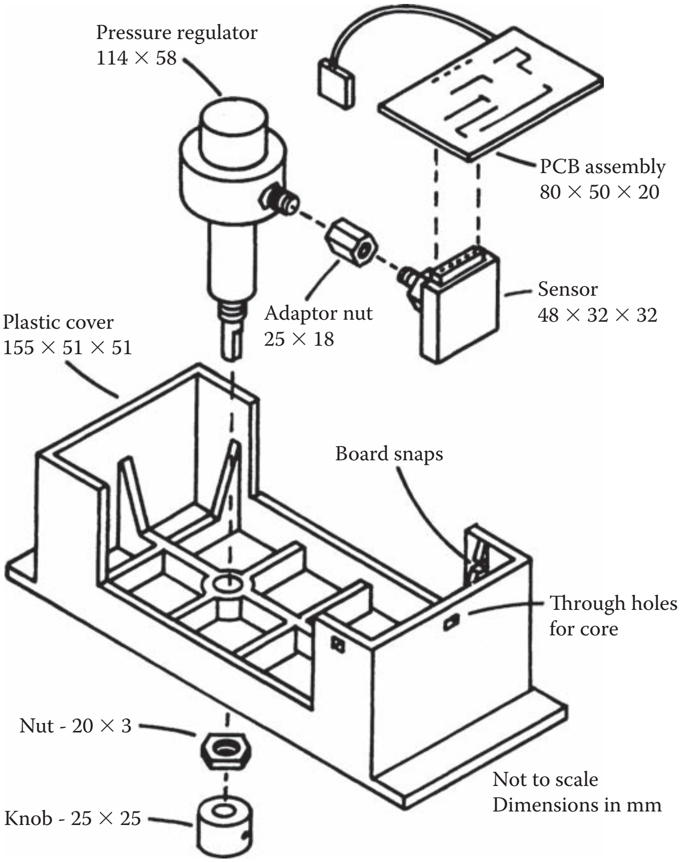


FIGURE 7.26 Conceptual redesign of the controller assembly.

We have now identified design changes that could result in saving at least 149.4 sec of assembly time, which constitutes almost 66% of the total. In addition, several items of hardware would be eliminated, resulting in reduced part costs. Figure 7.26 shows a conceptual redesign of the controller in which all the proposed design changes have been made, and Figure 7.27 presents the corresponding revised worksheet. The total assembly time is now approximately 84 sec, and the DFA index is increased to almost 18%, a fairly respectable figure for this type of assembly. Of course, the designer or design team must now consider the technical and economic consequences of the proposed design.

Most importantly, there is the effect on the cost of the parts. However, experience shows, and this example would be no exception, that the saving from parts cost reduction would be greater than the saving in assembly costs, the latter being $1.20.

It should be realized that the documented savings in materials, manufacturing, and assembly represent direct costs. To obtain a true picture, overheads must be

Item name	Number of items	Manual handling code	Handling time per item, s	Manual insertion code	Insertion time per item, s	Total operation time, s	Figures for min. parts	Description
1. Pressure regulator	1	30	1.95	00	1.50	3.45	1	Place in fixture
2. Plastic cover	1	30	1.95	06	5.50	7.45	1	Add and hold down
3. Nut	1	00	1.13	39	8.00	9.13	0	Add and screw fasten
4. Knob assembly	1	30	1.95	08	6.50	8.45	1	Add and screw fasten
5. Screw fastening	1			92	5.00	5.00		Operation
6. Reorientation	1			98	9.00	9.00		Reorient
7. Apply tape	1			99	12.00	12.00		Operation
8. Adapter nut	1	10	1.50	49	10.50	12.00	0	Add and screw fasten
9. Sensor sub.	1	30	1.95	39	8.00	9.90	1	Add and screw fasten
10. PCB assembly	1	83	5.60	30	2.00	7.60	1	Add and snap fit
Totals	**10**					**83.98**	**5**	

FIGURE 7.27 Completed analysis for the controller assembly redesign.

added, and these can often amount to 200% or more. In addition, there are other savings more difficult to quantify. For example, when a part such as the metal frame is eliminated, all associated documentation, including part drawings, is also eliminated. Also, the part cannot be misassembled or fail in service, factors that lead to improved reliability, maintainability, and quality of the product. It is not surprising, therefore, that many U.S. companies have been able to report annual savings measured in millions of dollars as a result of the application of the DFA analysis method described here.

7.17 FURTHER GENERAL DESIGN GUIDELINES

Some guidelines or design rules for the manual handling and insertion of parts were listed earlier. However, it is possible to identify a few more general guidelines that arise particularly from the application of the minimum parts criteria, many of which found application in the analysis of the controller.

1. *Avoid connections.* If the only purpose of a part or assembly is to connect A to B, then try to locate A and B at the same point. Figure 7.28 illustrated this guideline. Here, the two connected assemblies are rearranged to provide increasing assembly and manufacturing efficiency. Also, two practical examples occurred during the analysis of the controller when it was found that the entire tube assembly could be eliminated and that the wires from the PCB assembly to the connector were not necessary (Figure 7.24).

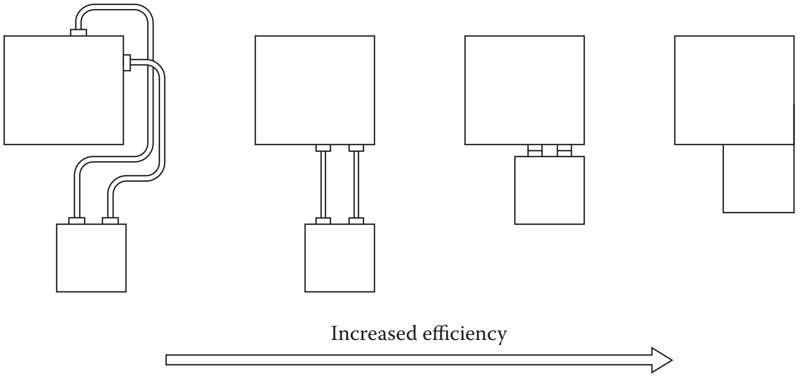


FIGURE 7.28 Rearrangement of connected items to improve assembly efficiency and reduce costs.

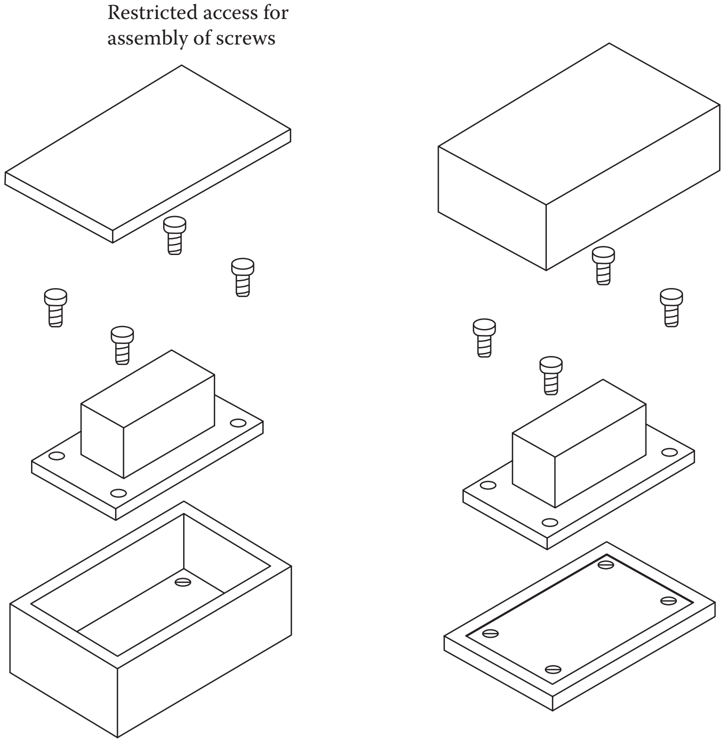


FIGURE 7.29 Design concept to provide easier access during assembly.

2. *Design so that access for assembly operations is not restricted.* Figure 7.29 shows two alternative design concepts for a small assembly. In the first concept, the installation of the screws would be very difficult because of the restricted access within the box-shaped base part. In the second concept, access is relatively unrestricted because the assembly is built up on the flat base part.

   An example of this type of problem occurred in the controller analysis when the screws holding the metal frame assembly in the plastic cover were installed (item 21, Figure 7.25).
3. *Avoid adjustments.* Figure 7.30 shows two parts of different materials secured by two screws in such a way that adjustment of the overall length of the assembly is necessary. If the assembly was replaced by one part manufactured from the more expensive material, difficult and costly operations would be avoided. These savings would probably more than offset the increase in material costs.
4. *Use kinematic design principles.* There are many ways in which the application of kinematic design principles can reduce manufacturing

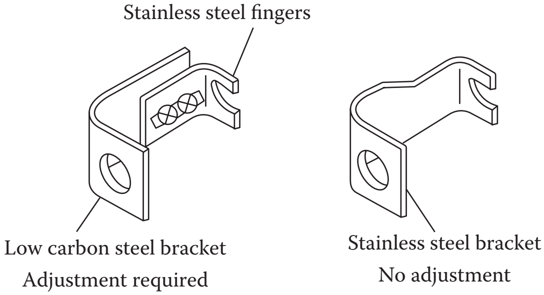


FIGURE 7.30 Design to avoid adjustment during assembly.

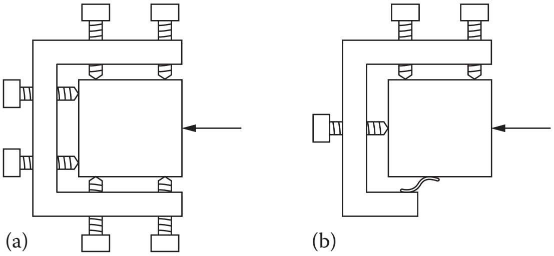


FIGURE 7.31 Overconstraint leads to unnecessary complexity in product design: (a) overconstrained design; (b) sound kinematic design.

> and assembly costs. Invariably, when located parts are overconstrained, it is necessary either to provide a means of adjustment for the constraining items or to employ more accurate machining operations. Figure 7.31a shows an example in which six point constraints are used to locate the square block in the plane of the page. Each constraint requires adjustment. According to kinematic design principles, only three point constraints are needed, together with closing forces. Clearly, the redesign shown in Figure 7.31b is simpler, requiring fewer parts, fewer assembly operations, and less adjustment.

In many circumstances, designs in which overconstraint is involved result in redundant parts. In the design involving overconstraint in Figure 7.32, one of the pins is redundant. However, the application of the minimum parts criteria to the design with a single pin would suggest combining the pin with one of the major parts and combining the washer with the nut.

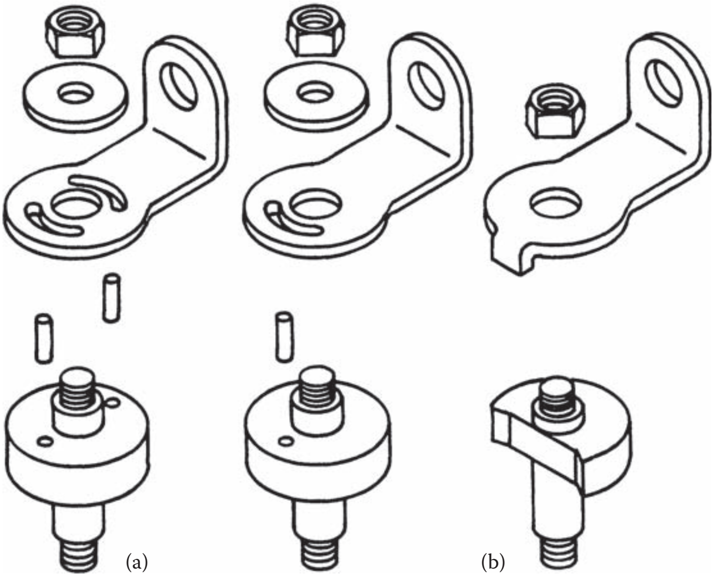


FIGURE 7.32 Overconstraint leads to redundancy of parts: (a) overconstraint; (b) kinematically sound.

REFERENCES

1. Militzer, R.W., Needed: Manufacturing Input to Product Design, President's Message, *Manufacturing Engineering*, Vol. 82, February 1979.
2. Boothroyd, G. and Dewhurst, P., Design for Assembly Software, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986.
3. Boothroyd, G., Design for Economic Manufacture, *Annals of the CIRP*, Vol. 28, No. 1, p. 345.
4. Yoosufani, Z. and Boothroyd, G., Design of Parts for Ease of Handling, Report #2, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, September 1978.
5. Boothroyd G., Design for Manual Handling and Assembly, Report #4, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, September 1979.
6. Yoosufani, Z., Ruddy, M., and Boothroyd, G., Effect of Part Symmetry on Manual Assembly Times, *Journal of Manufacturing Systems*, Vol. 2, No. 2, 1983, pp. 189–195.
7. Seth, B. and Boothroyd, G., Design for Manual Handling, Report #9, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, January 1979.
8. Ho, C. and Boothroyd, G., Avoiding Jams During Assembly, *Machine Design*, Technical Brief, January 25, 1979.
9. Ho, C. and Boothroyd, G., Reducing Disk-Assembly Problems, *Machine Design*, Technical Brief, March 8, 1979.

10. Ho, C. and Boothroyd, G., Design of Chamfers for Ease of Assembly, *Proceedings of the 7th North American Metalworking Conference*, S.M.E., May 1979, p. 345.
11. Fujita, T. and Boothroyd, G., Data Sheets and Case Study for Manual Assembly, Report #16, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, April 1982.
12. Yang, S.C. and Boothroyd, G., Data Sheets and Case Study for Manual Assembly, Report #15, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, December 1981.
13. Dvorak, W.A. and Boothroyd, G., Design for Assembly Handbook, Report #11, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, December 1980.
14. De Lisser, W.A. and Boothroyd, G., Analysis of Product Designs for Ease of Manual Assembly — A Systematic Approach, Report #17, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, May 1982.
15. Ellison, B. and Boothroyd, G., Applying Design for Assembly Handbook to Reciprocating Power Saw and Impact Wrench, Report #10, Department of Mechanical Engineering, University of Massachusetts, Amherst, MA, August 1980.
16. Karger, W. and Bayha, F.H., *Engineered Work Measurement*, Industrial Press, New York, 1966.
17. Raphael, D.L., A Study of Positioning Movements, Research Report 109, MTM Association of Standards and Research, Fairlawn, NJ, 1957.
18. Quick, J.H., *Work Factor Time Standards*, McGraw-Hill, New York, 1962.
19. Raphael, D.L., A Study of Arm Movements Involving Weight, Research Report #108, MTM Association of Standards and Research, Fairlawn, NJ, 1957.

8 Product Design for High-Speed Automatic Assembly and Robot Assembly

8.1 INTRODUCTION

Although design for assembly is an important consideration for manually assembled products and can reap enormous benefits, it is a vital consideration when a product is to be assembled automatically. The simple example shown in Figure 8.1 serves to illustrate this. The slightly asymmetrical screwed part would not present significant problems in manual handling and insertion whereas, for automatic handling, an expensive vision system would be needed to recognize its orientation. For economic automatic assembly, therefore, careful consideration of product structure and component part design is essential. In fact, it can be said that one of the advantages of introducing automation in the assembly of a product is that it forces a reconsideration of its design, thus reaping not only the benefits of automation but also those of improved product design. Not surprisingly, the savings resulting from product redesign will often outweigh those resulting from automation.

The example of the part in Figure 8.1 illustrates a further point. The principal problems in applying automation usually involve the automatic handling of the parts rather than their insertion into the assembly. To quote someone experienced

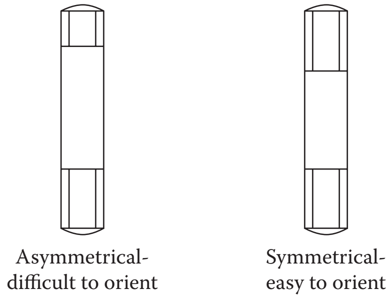


FIGURE 8.1 Design change to simplify automatic feeding and orienting.

in the subject of automatic assembly, “if a part can be handled automatically, then it can usually be assembled automatically.” This means that, when we consider design for automation, we will be playing close attention to the design of the parts for ease of automatic feeding and orienting.

In considering manual assembly, we were concerned with prediction of the time taken to accomplish the various tasks such as grasp, orient, insert, and fasten. Then, from knowledge of the assembly worker’s labor rate, we could estimate the cost of assembly. In automatic assembly, the time taken to complete an assembly does not control the assembly cost. Rather it is the rate at which the assembly machine or system cycles because, if everything works properly, a complete assembly is produced at the end of each cycle. Then, if the total rate (cost per unit time) for the machine or system and all the operators is known, the assembly cost can be calculated after allowances are made for downtime. Thus, we shall be concerned mainly with the cost of all the equipment, the number of operators and technicians, and the assembly rate at which the system is designed to operate. However, so that we can identify problems associated with particular parts, we shall need to apportion the cost of product assembly between the individual parts and, for each part, we shall need to know the cost of feeding and orienting and the cost of automatic insertion using the cycle time of the machine as a basis.

In the following, we shall look first at product design for high-speed automatic assembly using special-purpose equipment, and then we shall consider product design for robot assembly (i.e., using general-purpose equipment).

8.2 DESIGN OF PARTS FOR HIGH-SPEED FEEDING AND ORIENTING

The cost of feeding and orienting parts will depend on the cost of the equipment required and on the time interval between delivery of successive parts. The time between delivery of parts is the reciprocal of the delivery rate and will be nominally equal to the cycle time of the machine or system. If we denote the required delivery or feed rate F_r (parts/min), then the cost C_f of feeding each part will be given by

$$C_f = (60/F_r)R_f \text{ cents} \tag{8.1}$$

Where R_f is the cost (cents/sec) of using the feeding equipment.

Using a simple payback method for estimation of the feeding equipment rate R_f, this is given by

$$R_f = (C_F E_o)/(5760 P_b S_n) \text{ cents/sec} \tag{8.2}$$

Where C_F is the feeder cost in dollars, E_o the equipment factory overhead ratio, P_b the payback period in months, and S_n the number of shifts worked per day.

For example, if we assume that a standard vibratory-bowl feeder costs \$5K after installation and debugging, that the payback period is 30 months with two shifts working, and that the factory equipment overheads are 100% ($E_o = 2$), we get

$$R_f = (5000 \times 2)/(5760 \times 30 \times 2) = 0.03 \text{ cents/sec}$$

In other words, it would cost 0.03 cents to use the equipment for 1 sec. Suppose that we take this figure as the rate for a "standard" feeder, and we assign a relative cost factor C_r to any feeder under consideration, then Equation 8.1 becomes

$$C_f = 0.03(60/F_r)C_r \text{ cents} \tag{8.3}$$

Thus, we see that the feeding cost per part is inversely proportional to the required feed rate and proportional to the feeder cost.

To describe these results in simple terms, we can say that, for otherwise identical conditions, it would cost twice as much to feed each part to a machine with a 6-sec cycle compared with the cost for a machine with a 3-sec cycle. This illustrates why it is difficult to justify feeding equipment for assembly systems with long cycle times.

The second result can be simply stated: for otherwise constant conditions, it would cost twice as much to feed a part using a feeder costing \$10k compared to a feeder costing \$5k.

If the feeding cost given by Equation 8.3 and the required feed rate F_r are plotted on logarithmic scales, a linear relationship results, as shown in Figure 8.2. However, it appears that the faster the parts are required, the lower the feeding cost. This is true only as long as there is no limit on the speed at which a feeder can operate. Of course, there is always an upper limit to the feed rate obtainable

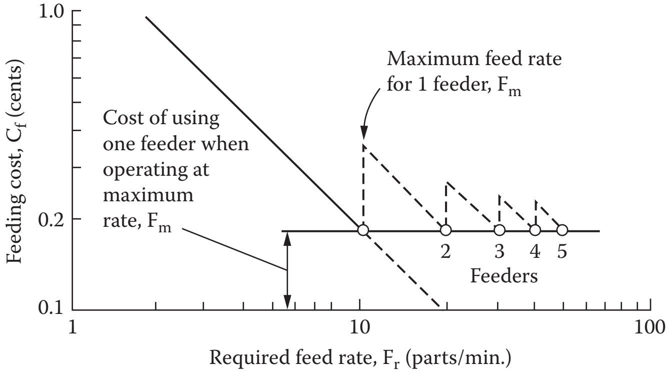


FIGURE 8.2 Effect of required feed rate on feeding cost.

from a particular feeder. We shall denote this maximum feed rate by F_m and consider the factors that affect its magnitude. Before doing so, however, we will look at its effect through an example.

Suppose the maximum feed rate from our feeder is 10 parts/min. Then, if parts are required at a rate of 5 parts/min, the feeder can simply be operated more slowly, involving an increased feeding cost, as given by Equation 8.3 and illustrated in Figure 8.2. However, suppose parts are required at a rate of 20 parts/min. In this case, two feeders could be used, each delivering parts at a rate of 10 parts/min. However, the feeding cost per part using two feeders to give twice the maximum feed rate will be the same as one feeder delivering parts at its maximum feed rate. In other words, if the required feed rate is greater than the maximum feed rate obtainable from one feeder, the feeding cost becomes constant and equal to the cost of feeding when the feeder is operating at its maximum rate. This is shown in Figure 8.2 by the horizontal line. In reality, this line will be saw-toothed, but it can reasonably be assumed that irregularities can be smoothed by spending a little more on feeders to improve their performance when necessary.

From this discussion, we can say that Equation 8.3 holds true only when the required feed rate F_r is less than the maximum feed rate F_m and, when this is not the case, the feeding cost is given by

$$C_f = 0.03(60/F_m)C_r \text{ cents} \tag{8.4}$$

Now, the maximum feed rate F_m is given by

$$F_m = 1500E/\ell \text{ parts/sec} \tag{8.5}$$

where E is the orienting efficiency for the part and ℓ (mm) is its overall dimension in the direction of feeding and where it is assumed that the feed speed is 25 mm/s.

To illustrate the meaning of the orienting efficiency E, we can consider the feeding of dies (cubes with faces numbered 1–6). Suppose that, if no orientation is needed, the dies can be delivered at a rate of 1 per sec from a vibratory-bowl feeder. However, if only those dies with the 6 side uppermost were of interest, a vision system could be employed to detect all other orientations and a solenoid-operated pusher could be used to reject them. In this case, the delivery rate would fall to an average of one die every 6 sec or a feed rate of 1/6 per sec. If the factor 1/6 is defined as the orienting efficiency, it can be seen that the maximum feed rate is proportional to the orienting efficiency (Equation 8.5).

Now, let us suppose that our dies were doubled in size and that the feed speed or conveying velocity on the feeder track was unaffected. It would then take twice as long to deliver each die. In other words, the maximum feed rate is inversely proportional to the length of the part in the feeding direction (Equation 8.5).

Equation 8.4 shows that, when $F_r > F_m$, the feeding cost per part is inversely proportional to F_m. It follows that, under these circumstances, the cost of feeding is inversely proportional to the orienting efficiency and proportional to the length of the part in the feeding direction.

This latter relationship illustrates why automatic feeding and orienting methods are applicable only to "small" parts. In practice, this means that parts larger than about 3 in. in their major dimension cannot usually be fed economically

The designer, when considering the design of a part and its feeding cost, knows the required feed rate and the dimensions of the part. Thus F_r and ℓ are known. The remaining two parameters that affect feeding cost, namely, the orienting efficiency E and the relative feeder cost C_r, depend on the part symmetry and the types of features that define its orientation. In Appendix D, detailed information is given, which allows the feed rate to be estimated for a wide variety of parts and feeding methods. This feed rate can be considered to be the maximum feed rate, F_m.

Alternatively, for quick estimates of feeding cost, a classification system for part symmetry and features has been developed [1] and, for each part classification, the average magnitudes of E and C_r have been determined [2]. This classification system and data are presented in Figure 8.3–Figure 8.5. Figure 8.3 shows how parts are categorized into basic types, either rotational or nonrotational. For rotational parts, their cylindrical envelopes are classified as disks, short cylinders, or long cylinders. In the case of nonrotational parts, the subcategories are flat,

Rotational	Discs	$L/D < 0.8$	0
	Short cylinders	$0.8 \leq L/D \leq 1.5$	1
	Long cylinders	$L/D > 1.5$	2
Nonrotational	Flat	$A/B \leq 3$ $A/C > 4$	6
	Long	$A/B > 3$	7
	Cubic	$A/B \leq 3$ $A/C \leq 4$	8

FIGURE 8.3 First digit of geometrical classification of parts for automatic handling. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

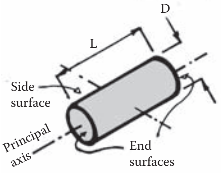
Notes:

1. A part whose basic shape is a cylinder or regular prism whose cross section is a regular polygon of five or more sides is called a *rotational part*. In addition, triangular or square parts that repeat their orientation when rotated about their principal axis through angles of 120° or 90°, respectively, are rotational parts.
2. L is the length and D is the diameter of the smallest cylinder that can completely enclose the part.
3. A is the length of the longest side, C is the length of the shortest side and B is the length of the intermediate side of the smallest rectangular prism that can completely enclose the part.

AUTOMATIC HANDLING-DATA FOR ROTATIONAL PARTS
(first digit 0, 1 or 2)

KEY:

		E	C_r
First digit	0	0.3	1
	1	0.15	1.5
	2	0.45	1.5



				Part is symmetrical about its principal axis (BETA symmetric) (see note 2)	Part is not BETA symmetric (code the main feature or features requiring orientation about the principal axis)						
					BETA asymmetric projections, steps, or chamfers (can be seen in silhouette)			BETA asymmetric grooves or flats (can be seen in silhouette)			Slightly asymmetric or small features less than D/10 and L/10 or holes or recesses which cannot be seen in outer shape of silhouette
					On side surface only	On end surface(s) only	On both side and end surface(s)	Through groove or flat can be seen in end view	Through groove can be seen in side view		
									On end surface	On side surface	
				0	2	3	4	5	6	7	8
Part is ALPHA symmetric (see note 1)			0	0.7 1 0.7 1 0.9 1	0.3 1 0.15 1 0.45 1	0.5 1 0.2 1 0.9 2	0.3 1 0.15 1 0.45 1	0.35 1 0.2 1 0.9 1	0.2 1 0.2 1 0.9 2	0.5 1 0.2 1 0.9 2	
Part is not ALPHA symmetric (code the main feature or features requiring end-to-end orientation) (see note 1)	Part can be fed in a slot supported by large end or protruding flange with center of mass below supporting surfaces		1	0.4 1 0.3 1 0.9 1	0.2 1 0.1 1 0.45 1	0.25 1 0.1 1 0.9 2	0.2 1 0.1 1 0.45 1	0.2 1 0.1 1 0.9 1	0.1 1 0.1 1 0.9 2	0.25 1 0.1 1 0.9 1	
	BETA symmetric steps or chamfers on external surfaces (see note 3)		2	0.4 1 0.3 1 0.75 1	0.15 1 0.1 1.5 0.37 1.5	0.25 1 0.1 1.5 0.25 3	0.15 1 0.1 1.5 0.37 1.5	0.35 1 0.2 1.5 0.5 1	0.1 1 0.05 1.5 0.5 3	0.25 1 0.1 1.5 0.5 2	
	BETA symmetric grooves holes or recesses (see note 3)	On both side and end surface(s)	3	0.5 1 0.2 1 0.85 1	0.15 1 0.1 1.5 0.43 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.43 1.5	0.2 1 0.1 1.5 0.5 1	0.1 1 0.05 1.5 0.5 2	0.25 1 0.1 1.5 0.5 2	–MANUAL HANDLING REQUIRED–
		On side surface only	4	0.5 1 0.1 1 0.85 1	0.15 1 0.1 1.5 0.43 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.43 1.5	0.2 1 0.1 1.5 0.5 1	0.1 1 0.05 1.5 0.5 2	0.25 1 0.1 1.5 0.5 2	
		On end surface(s) only	5	0.5 1 0.2 1 0.6 1	0.15 1 0.1 1.5 0.27 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.27 1.5	0.2 1 0.1 1.5 0.45 1	0.1 1 0.05 1.5 0.45 2	0.25 1 0.1 1.5 0.45 2	
	BETA symmetric hidden features with no corresponding exposed features (see note 4)		6	0.6 1	0.27 1.5	0.25 2	0.27 1.5	0.45 1	0.45 2	0.45 2	
	BETA asymmetric features on side or end surface(s)		7		0.27 2	0.25 1 0.1 1.5 0.25 3	0.1 1 0.05 1.5 0.27 2	0.1 3	0.1 1 0.05 1.5 0.5 3	0.25 1 0.1 1.5 0.5 3	
	Slightly asymmetric or small features; amount of asymmetry or feature size less than D/10 and L/10		8	–MANUAL HANDLING REQUIRED–							

FIGURE 8.4 Second and third digits of geometrical classification for rotational parts. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

FIGURE 8.4 (CONTINUED

Notes:

1. A rotational part is alpha symmetric if it does not require orienting end-to-end. If a part can only be inserted into the assembly in one direction then it is referred to as "not alpha symmetric."
2. A beta-symmetric part has rotational symmetry and therefore does not require orienting about its principal axis.
3. A beta-symmetric step, chamfer or groove is a concentric reduction or increase in diameter; its cross section can be circular or any regular polygon. Less significant features should be ignored.
4. Parts in this category have an alpha-symmetric external shape, but the internal surface (composed perhaps of cavities, counterbores, grooves, etc.) requires that the part be oriented end to end.

long, or cubic, depending on the dimensions of the sides of the rectangular envelope.

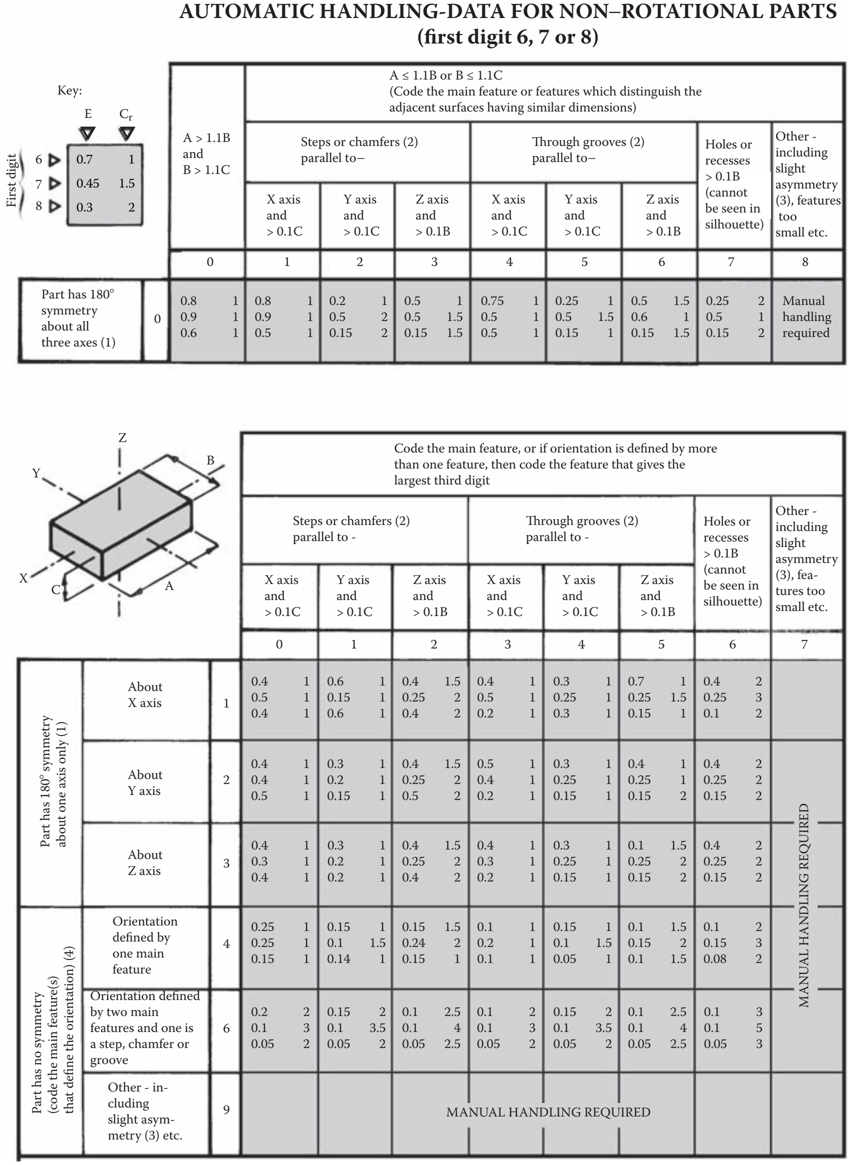
Figure 8.3 gives the first digit of a three-digit shape code. Figure 8.4 shows how the second and third digits are determined for rotational parts (first digit 0, 1, or 2) and gives the corresponding values of the orienting efficiency E and the relative feeder cost C_r. Similarly, Figure 8.5 shows how the second and third digits are determined for nonrotational parts (first digit 6, 7, or 8). The geometrical classification system was originally devised by Boothroyd and Ho [1] as a means of cataloging solutions to feeding problems.

8.3 EXAMPLE

Suppose the part shown in Figure 8.6 is to be delivered to an automatic assembly station working at a 5-sec cycle. We will now use the classification system and data base to determine the feeding cost, and we will assume that the cost of delivering simple parts at 1/sec using our "standard" feeder is 0.03 cents/part.

First, we must determine the classification code for our part. Figure 8.6 shows that the rectangular envelope for the part has dimensions $A = 30$, $B = 20$, and $C = 15$ mm.

Thus, $A/B = 1.5$ and $A/C = 2$. Referring to Figure 8.3 we see that, as A/B is less than 3 and A/C is less than 4, the part is categorized as cubic nonrotational and is assigned a first digit of 8. Turning to Figure 8.5, which provides data for nonrotational parts, we first determine that our example part has no rotational symmetry about any of its axes. Also, we must decide whether the orientation of the part can be determined by one main feature. Looking at the silhouette of the part in the X direction, we see a step or projection in the basic rectangular shape, and we realize that this feature alone can always be used to determine the orientation of the part. This means that if the silhouette in the X direction is oriented as shown in Figure 8.6, the part can be in only one orientation and, therefore, the second digit of the classification is 4. However, either the groove apparent in the view in the Y direction and the step seen in the view in the Z direction can also be used to determine the orientation of the part. The procedure



AUTOMATIC HANDLING-DATA FOR NON–ROTATIONAL PARTS
(first digit 6, 7 or 8)

Key:

First digit	E	C_r
6	0.7	1
7	0.45	1.5
8	0.3	2

		A > 1.1B and B > 1.1C	A ≤ 1.1B or B ≤ 1.1C (Code the main feature or features which distinguish the adjacent surfaces having similar dimensions)							
			Steps or chamfers (2) parallel to–			Through grooves (2) parallel to–			Holes or recesses > 0.1B (cannot be seen in silhouette)	Other - including slight asymmetry (3), features too small etc.
			X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
		0	1	2	3	4	5	6	7	8
Part has 180° symmetry about all three axes (1)	0	0.8 1 0.9 1 0.6 1	0.8 1 0.9 1 0.5 1	0.2 1 0.5 2 0.15 2	0.5 1 0.5 1.5 0.15 1.5	0.75 1 0.5 1 0.5 1	0.25 1 0.5 1.5 0.15 1	0.5 1.5 0.6 1 0.15 1.5	0.25 2 0.5 1 0.15 2	Manual handling required

			Code the main feature, or if orientation is defined by more than one feature, then code the feature that gives the largest third digit							
			Steps or chamfers (2) parallel to -			Through grooves (2) parallel to -			Holes or recesses > 0.1B (cannot be seen in silhouette)	Other - including slight asymmetry (3), features too small etc.
			X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
			0	1	2	3	4	5	6	7
Part has 180° symmetry about one axis only (1)	About X axis	1	0.4 1 0.5 1 0.4 1	0.6 1 0.15 1 0.6 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.5 1 0.2 1	0.3 1 0.25 1 0.3 1	0.7 1 0.25 1.5 0.15 1	0.4 2 0.25 3 0.1 2	MANUAL HANDLING REQUIRED
	About Y axis	2	0.4 1 0.4 1 0.5 1	0.3 1 0.2 1 0.15 1	0.4 1.5 0.25 2 0.5 2	0.5 1 0.4 1 0.2 1	0.3 1 0.25 1 0.15 1	0.4 1 0.25 1 0.15 2	0.4 2 0.25 2 0.15 2	
	About Z axis	3	0.4 1 0.3 1 0.4 1	0.3 1 0.2 1 0.2 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.3 1 0.2 1	0.3 1 0.25 1 0.15 1	0.1 1.5 0.25 2 0.15 2	0.4 2 0.25 2 0.15 2	
Part has no symmetry (code the main feature(s) that define the orientation) (4)	Orientation defined by one main feature	4	0.25 1 0.25 1 0.15 1	0.15 1 0.1 1.5 0.14 1	0.15 1.5 0.24 2 0.15 1	0.1 1 0.2 1 0.1 1	0.15 1 0.1 1.5 0.05 1	0.1 1.5 0.15 2 0.1 1.5	0.1 2 0.15 3 0.08 2	
	Orientation defined by two main features and one is a step, chamfer or groove	6	0.2 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 3 0.1 5 0.05 3	
	Other - including slight asymmetry (3) etc.	9	MANUAL HANDLING REQUIRED							

FIGURE 8.5 Second and third digits of geometrical classification for nonrotational parts. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

FIGURE 8.5 (CONTINUED

Notes:

1. A rotational symmetry of 180° about an axis means that the same orientation of the part will be repeated only once by rotating the part through 180° about that axis.
2. Steps, chamfers, or through grooves are features that can be seen in silhouette.
3. Exposed features are prominent but the asymmetry caused by these features is less than 0.1 of the appropriate envelope dimension. For a part that has 180° rotational symmetry about a certain axis, slight asymmetry implies that the part has almost 90° rotational symmetry about that axis.
4. A part having no rotational symmetry means that the same orientation of the part will not be repeated by rotating the part through any angle less than 360° about any one of the three axes X, Y, or Z.

A main feature is a feature that is chosen to define the orientation of the part. All the features that are chosen to completely define the orientation of the part should be necessary and sufficient for the purpose.

Often, features arise in pairs or groups and the pair or group of features is symmetric about one of the three axes X, Y, or Z. In this case, the pair or group of features should be regarded as one main feature. Using this convention, two main features at most are needed to completely define the orientation of a part.

now is to select the feature giving the smallest digit of the third classification; in this case, it is the step seen in the X direction. Thus, the third digit is 0, giving a three-digit code of 840 and corresponding values of orienting efficiency $E = 0.15$ and relative feeder cost $C_r = 1$.

Because the longest part dimension ℓ is 30mm and the orienting efficiency E is 0.15, Equation 8.5 gives the maximum feed rate obtainable from one feeder, thus,

$$F_m = 1500E/\ell = 1500 \times 0.15/30 = 7.5 \text{ parts/min.}$$

Now, from the cycle time of 5 sec. the required feed rate F_r is 12 parts/min, which is slightly higher than F_m. Therefore, because $F_r > F_m$, we use Equation 8.4 and, because $C_r = 1$, we get a feeding cost of

$$C_f = 0.03\ (60/F_m)C_r = 0.03\ (60/7.5) \times 1 = 0.24 \text{ cents}$$

8.4 ADDITIONAL FEEDING DIFFICULTIES

In addition to the problems of using the geometric features of the part to orient it automatically, other part characteristics can make feeding particularly difficult. For example, if the edges of the parts are thin, shingling or overlapping can occur during feeding, which leads to problems with the orienting devices on the vibratory-bowl feeder track (Figure 8.7)

Many other features can affect the difficulty of feeding the part automatically and can lead to considerable increases in the cost of developing the automatic

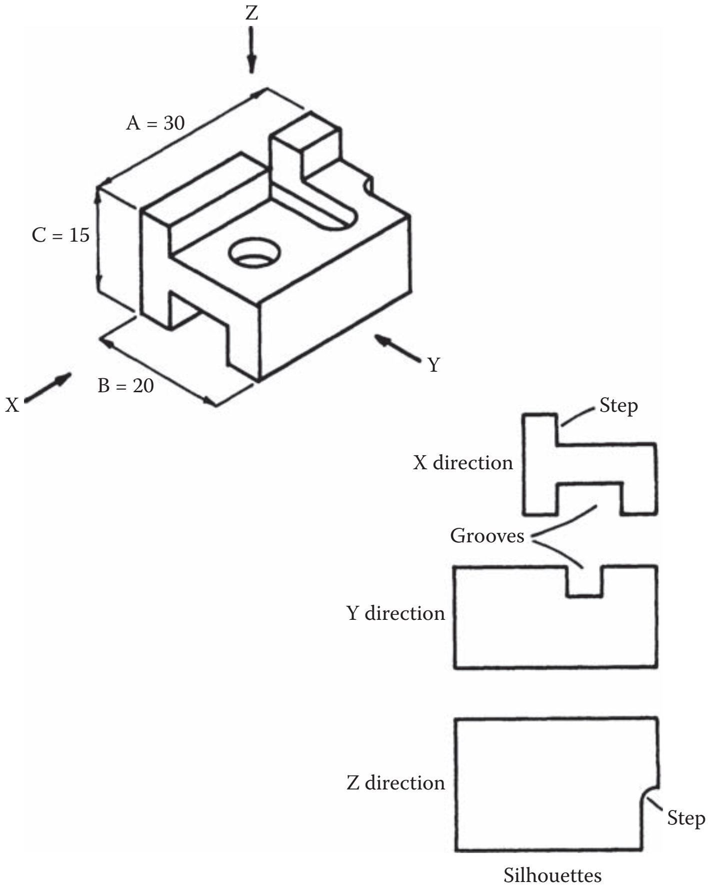


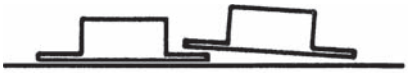
FIGURE 8.6 Sample part.

feeding device. These features can also be classified as shown in Figure 8.8 where, for each combination of features, an approximate additional relative feeder cost is given that should be taken into account in estimating the cost of automatic feeding.

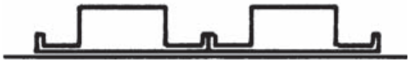
8.5 HIGH-SPEED AUTOMATIC INSERTION

If a part can be sorted from bulk and delivered to a convenient location correctly oriented, a special-purpose mechanism or workhead can usually be designed that will place it in the assembly. Such workheads can generally be designed to operate on a cycle as short as 1 sec. Thus, for assembly machines operating on cycles greater than 1 sec, the automatic insertion cost C_i will be given by

$$C_i = (60/F_r)R_i \tag{8.6}$$



Difficult to feed - parts overlap



Easy to feed

FIGURE 8.7 Parts that shingle or overlap on the feeder track.

where F_r is the required assembly rate (or feed rate) of parts and R_i is the cost (cents/sec) of using the automatic workhead.

Again, when a simple payback method for estimation of the equipment rate R_i is used, this is given by

$$R_i = (W_c E_o)/(5760\ P_b S_n)\ \text{cents/sec} \tag{8.7}$$

where W_c is the workhead cost in dollars, E_o the equipment factory overhead ratio, P_b the payback period in months, and S_n the number of shifts worked per day.

If we assume that a standard workhead costs \$10k after installation and debugging, that the payback period is 30 months with two shifts working, and that the factory equipment overheads are 100% ($E_o = 2$), we get

$$R_i = (10{,}000 \times 2)/(5760 \times 30 \times 2) = 0.06\ \text{cents/sec}$$

In other words, it would cost 0.06 cents to use the equipment for 1 sec. If we take this figure as the rate for a "standard" workhead and we assign a relative cost factor W_c to any workhead under consideration, Equation 8.6 becomes

$$C_i = 0.06\ (60/F_r)W_c \tag{8.8}$$

Thus, the insertion cost is inversely proportional to the required assembly rate and proportional to the workhead cost.

The designer considering the design of a part knows the required assembly rate F_r. For presentation of relative workhead costs, a classification system for automatic insertion similar to that for manual insertion has been devised [2] and is shown in Figure 8.9. It can be seen that this classification system is similar to that for manual insertion of parts, except that the first digit is determined by the insertion direction rather than by obstructed access or restricted vision.

AUTOMATIC HANDLING-ADDITIONAL FEEDER COSTS

FIGURES TO BE ADDED TO C_r					Parts will not tangle or nest				Tangle or nest but not severely				Severely nest	Severely tangle
					Not light		Light		Not light		Light			
					Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky		
					0	1	2	3	4	5	6	7	8	9
Parts are small and non-abrasive	Parts do not tend to overlap during feeding	Not delicate	Non-flexible	0	0	1	2	3	2	3	3	4	MANUAL HANDLING REQUIRED	
			Flexible	1	2	3	4	5	4	5	5	6		
		Delicate	Non-flexible	2	1	2	3	4	3	4	4	5		
			Flexible	3	3	4	5	6	5	6	6	7		
	Parts tend to overlap during feeding	Not delicate	Non-flexible	4	2	3	3	4	4	5	4	5		
			Flexible	5	4	5	5	6	6	7	6	7		
		Delicate	Non-flexible	6	3	4	4	5	5	6	5	6		
			Flexible	7	5	6	6	7	7	8	7	8		

		Very small parts					Large parts				
		Rotational		Non-rotational			Rotational		Non-rotational		
		L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3 A/C > 4	A/B > 3	A/B ≤ 3 A/C ≤ 4	L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3 A/C > 4	A/B > 3	A/B ≤ 3 A/C ≤ 4
		0	1	2	3	4	5	6	7	8	9
Parts are very small or large but are nonabrasive	8	2	2	2	2	2	9	9	9	9	9

		Parts will not severely tangle or nest									Severely tangle or nest
		Small parts					Large parts		Very small parts		
		Orientation defined by geometric features			Orientation defined by non-geometric features		Orientation defined by geometric features	Orientation defined by non-geometric features	Orientation defined by geometric features	Orientation defined by non-geometric features	
		Non-flexible		Flexible	Do not overlap	Overlap					
		Do not overlap	Overlap								
		0	1	2	3	4	5	6	7	8	9
Abrasive parts	9	2	4	4			9		4		

FIGURE 8.8 Additional relative feeder costs for a selection of feeding difficulties. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

FIGURE 8.8 (CONTINUED

Notes:

Flexible. A part is considered flexible if the part cannot maintain its shape under the action of automatic feeding so that orienting devices cannot function satisfactorily.

Delicate. A part is considered delicate if damage may occur during handling, either due to breakage caused by parts falling from orienting sections or tracks onto the hopper base, or due to wear caused by recirculation of parts in the hopper. When wear is the criterion, a part would be considered delicate if it could not recirculate in the hopper for 30 min and maintain the required tolerance.

Sticky. If a force, comparable to the weight of a nontangling or nonnesting part, is required to separate it from bulk, the part is considered sticky.

Light. A part is considered too light to be handled by conventional hopper feeders if the ratio of its weight to the volume of its envelope is less than 1.5kN/m^3.

Overlap. Parts will tend to overlap in a feeder when an alignment of better than 0.2 mm is required to prevent shingling or overlapping during feeding in single file on a horizontal track.

Large. A part is considered to be too large to be readily handled by conventional hopper feeders when its smallest dimension is greater than 50 mm or if its maximum dimension is greater than 150 mm. A part is considered to be too large to be handled by a particular vibratory hopper feeder if L > d/8, where L is the length of the part measured parallel to the feeding direction and d is the feeder or bowl diameter.

Very small. A part is considered to be too small to be readily handled by conventional hopper feeders when its largest dimension is less than 3 mm. A part is considered to be too small to be readily handled by a particular vibratory hopper feeder if its largest dimension is less than the radius of the curved surface joining the hopper wall and the track surface measured in a plane perpendicular to the feeding direction.

Nest. Parts are considered to nest if they interconnect when in bulk causing orientation problems. No force is required to separate the parts when they are nested.

Severely nest. Parts are considered to severely nest if they interconnect and lock when in bulk and require a force to separate them.

Tangle. Parts are said to tangle if a reorientation is required to separate them when in bulk.

Severely tangle. Parts are said to severely tangle if they require manipulation to specific orientations and a force is required to separate them.

Abrasive. A part is considered to be abrasive if it may cause damage to the surface of the hopper feeding device unless these surfaces are specially treated.

8.6 EXAMPLE

If the part shown in Figure 8.6 is to be inserted horizontally into the assembly in the direction of arrow *Y* and is not easy to align and position and is not secured on insertion, the automatic insertion code is 12, giving a relative workhead cost of 1.6.

For a cycle time of 5 sec the assembly rate F_r is 12 parts/min, and Equation 8.8 gives an insertion cost of

$$C_i = 0.06\ (60/F_r)W_c = 0.06\ (60/12)\ 1.6 = 0.48 \text{ cents}$$

AUTOMATIC INSERTION-RELATIVE WORKHEAD COST, W_C

Key:

☐ PART ADDED but NOT SECURED

▨ PART SECURED IMMEDIATELY

▨ SEPARATE OPERATION

				0	1	2	3	6	7	8	9
				After assembly no holding down required to maintain orientation and location (5)				Holding down required during subsequent process(es) to maintain orientation and location (5)			
				Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)	
				No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to inser-tion (7)
No final securing is taking place (2)	Straight line insertion	From vertically above	0	1	1.5	1.5	2.3	1.3	2	2	3
		Not from vertically above (3)	1	1.2	1.6	1.6	2.5	1.6	2.1	2.1	3.3
	Insertion not straight line motion (4)		2	2	3	3	4.6	2.7	4	4	6.1

				0	1	2	3	4	5	6	7	8	9
				No screwing operation or plastic deformation immediately after insertion (snap or press fits, etc.)		Plastic deformation immediately after insertion						Screwing immediately after insertion	
						Plastic bending			Rivetting or similar plastic deformation				
						Easy to align and position (6)	Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)	Not easy to align or position (no features provided for the purpose)			
				Easy to align and position (6) no resistance to insertion	Not easy to align or position and/or resistance to insertion		No resistance to insertion	Resistance to insertion (7)		No resistance to insertion	Resistance to insertion (7)	Easy to align and position (6) no resistance to screwing	Not easy to align or position and/or resistance to screwing (7)
Addition of any part (1) where final securing is taking place	Straight line insertion	From vertically above	3	1.2	1.9	1.6	2.4	3.6	0.9	1.4	2.1	0.8	1.8
		Not from vertically above (3)	4	1.3	2.1	2.1	3.2	4.8	1	1.5	2.3	1.3	2
	Insertion not straight line motion (4)		5	2.4	3.8	3.2	4.8	7.2	1.8	2.8	4.2	1.6	3.6

		0	1	2	3	4	5	6	7	8	9
		Mechanical fastening processes (parts already in place)				Non-mechanical fastening processes (parts already in place)				Non-fastening processes	
		None or localized plastic deformation				Metallurgical processes					
							Additional material required				
		Bending or similar processes	Rivetting or similar processes	Screwing or other processes	Snap fit, snap clip, press fit, etc.	No additional of material (friction or resistance welding, etc.)	Soldering processes	Welding or brazing	Chemical processes (adhesive bonding etc.)	Manipulation of parts or sub-assembly (orienting, fitting, adjustment etc.)	Other processes (liquid insertion etc.)
Assembly process where all solid parts are in place or non-solids added or parts are manipulated	9	1.6	0.9	0.8	1.6	1.2	1.1	1.1	0.8	1.5	

FIGURE 8.9 Relative workhead costs W_c for a selection of automatic insertion situations. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

FIGURE 8.9 (CONTINUED

Notes:

1. A part is a solid or nonsolid element of an assembly added during an assembly process. A subassembly is considered a part if it is added during assembly. However, adhesive, fluxes, fillers, etc., used for joining parts are not considered to be parts.
2. Part addition involves part placing or insertion processes only. Part may be a fastener that is not securing any other part or parts immediately.
3. Placing or insertion of the part into the assembly necessitates access motions from a direction other than vertically above (e.g., from the side or from below, etc.).
4. Part cannot be placed or inserted by a simple single-axis straight-line motion. For example, part access may be obstructed requiring a change in the direction of motion during insertion.
5. Part is unstable after placement or insertion or during subsequent operations and will require gripping realignment or holding down until it is finally secured. *Holding down* refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to or during the next assembly operation or during transfer of the assembly to the next workstation. A part is *located* if it will not require holding down or realignment for subsequent operations, and it is only partially secured.
6. A part is easy to align and position if the position of the part is established by locating features on the part, or on its mating part, and insertion is facilitated by well-designed chamfers or similar features.
7. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For example, a press fit is an interferences fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

Thus, the total handling and insertion cost C_t for this part is

$$C_t = C_f + C_i = 0.24 + 0.48 = 0.72 \text{ cents}$$

8.7 ANALYSIS OF AN ASSEMBLY

To facilitate the analysis of a complete assembly, a worksheet similar to that used for manual assembly analysis can be employed. Figure 8.10 shows the exploded view of a simple assembly before and after redesign. The assumed average assembly rate of 9.6/min includes allowances for any down time due to faulty parts and for general working efficiency. Figure 8.11 presents the completed automatic assembly worksheets.

It can be seen that, in the original design, the gasket and cover must be handled and inserted manually because they cannot be oriented with respect to the two screw holes. The costs of manual assembly for these two items are entered on the worksheet using a burdened assembly worker rate of \$30/h.

The cost of parts handling, insertion and fastening (not including the cost of the transfer devices and any supervisors) has been reduced by redesign from 16.92 to 2.81 cents. The original design would require four automatic assembly

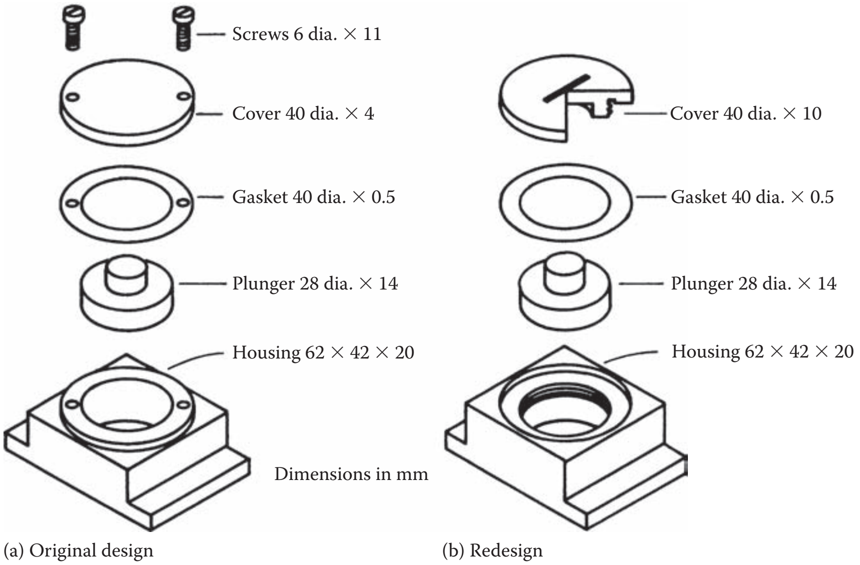


FIGURE 8.10 Simple assembly.

stations and two manual stations. The redesign would require only the four automatic stations resulting in further significant cost savings.

8.8 GENERAL RULES FOR PRODUCT DESIGN FOR AUTOMATION

The most obvious way to facilitate the assembly process at the design stage is to reduce the number of different parts to a minimum. This subject was covered in the preceding chapter, which dealt with manual assembly, where it was emphasized that simplification of the product structure can lead to substantial savings in assembly and, particularly, in the cost of the parts. When considering product design for automation, it is even more important to consider reduction in the number of separate parts. For example, the elimination of a part can eliminate a complete station on an assembly machine, including the parts feeder, the special workhead, and the associated portion of the transfer device. Hence, the reduction in necessary investment can be substantial when a product structure is simplified.

Apart from product simplification, automation can be facilitated by the introduction of guides and chamfers that directly facilitate assembly. Examples of this are given by Baldwin [3] and Tipping [4] in Figure 8.12 and Figure 8.13. In both examples, sharp corners are removed so that the part to be assembled is guided into its correct position during assembly and requires less control by the placement device.

Item no.	Name	Repeat count	Feed code	Orient efficiency E	Relative feeder cost C_r	Max. feed/min. F_m	Feeding cost C_f	Insertion code	Relative workhead cost W_c	Insertion cost C_i	Total cost C_t	Min. parts
1	Housing	1	83100	0.2	1	7.1	0.25	00	1	0.38	0.63	1
2	Plunger	1	02000	0.4	1	21.4	0.19	02	1.5	0.56	0.75	1
3	Gasket	1	00840	Manual assembly required							7.13	0
4	Cover	1	00800	Manual assembly required							6.67	1
5	Screw	2	21000	0.9	1	122.7	0.19	39	1.8	0.68	1.74	0
		6									16.92	3

(a) Original design

Item no.	Name	Repeat count	Feed code	Orient efficiency E	Relative feeder cost C_r	Max. feed/min. F_m	Feeding cost C_f	Insertion code	Relative workhead cost W_c	Insertion cost C_i	Total cost C_t	Min. parts
1	Housing	1	83100	0.2	1	7.1	0.25	00	1	0.38	0.63	1
2	Plunger	1	02000	0.4	1	21.4	0.19	02	1.5	0.56	0.75	1
3	Gasket	1	00040	0.7	3	26.3	0.56	00	1	0.38	0.94	0
4	Cover	1	02000	0.4	1	15	0.19	38	0.8	0.3	0.49	1
		4									2.81	3

(b) Redesign

FIGURE 8.11 Completed worksheets for high-speed automatic assembly analysis of the assemblies in Figure 8.10.

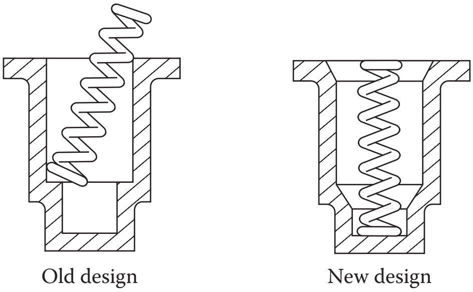


FIGURE 8.12 Redesign of part for ease of assembly. (From Baldwin, S.P., How to Make Sure of Easy Assembly, *Tool and Manufacturing Engineering*, May, 1966, p. 67. With permission.)

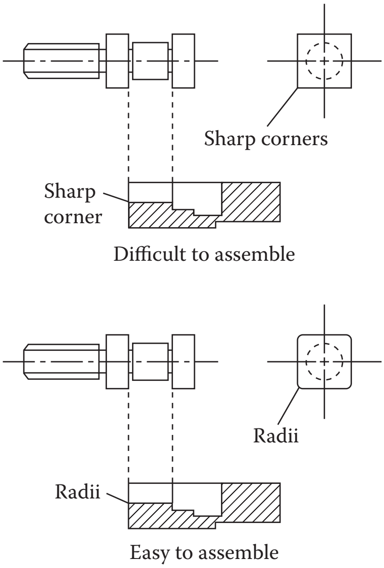


FIGURE 8.13 Redesign to assist assembly. (From Tipping, W.V., Component and Product Design for Mechanized Assembly, Conference on Assembly, Fastening and Joining Techniques and Equipment, Production Engineering Research Association, England, 1965. With permission.)

Further examples in this category can be found in the types of screws used in automatic assembly. Those screws that tend to centralize themselves in the hole give the best results in automatic assembly. Tipping [4] summarizes and grades the designs of screw points available as follows (Figure 8.14):

1. Rolled threat point: very poor location; does not centralize without positive control on the outside diameter of the screws

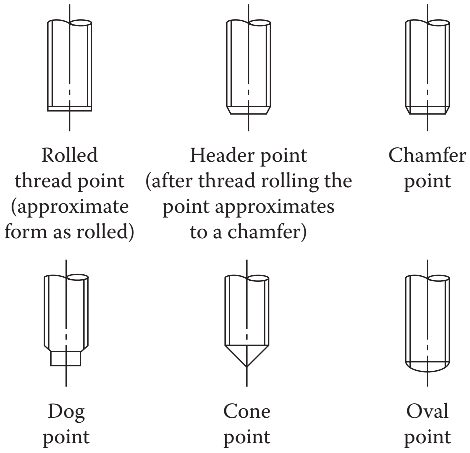

Rolled thread point (approximate form as rolled)
Header point (after thread rolling the point approximates to a chamfer)
Chamfer point
Dog point
Cone point
Oval point

FIGURE 8.14 Various forms of screw points. (From Tipping, W.V., Component and Product Design for Mechanized Assembly, Conference on Assembly, Fastening and Joining Techniques and Equipment, Production Engineering Research Association, England, 1965. With permission.)

2. Header point: only slightly better than point 1 if of correct shape
3. Chamfer point: reasonable to locate
4. Dog point: reasonable to locate
5. Cone point: very good to locate
6. Oval point: very good to locate

Tipping recommends that only the cone- and oval-point screws be used in automatic assembly.

Another factor to be considered in design is the difficulty of assembly from directions other than directly above. The aim of the designer should be to allow for assembly in sandwich or layer fashion, with each part placed on top of the previous one. The biggest advantage of this method is that gravity is useful in the feeding and placing of parts. It is also desirable to have workheads and feeding devices above the assembly station, where they will be accessible in the event of a fault due to the feeding of a defective part. Assembly from above may also assist in the problem of keeping parts in their correct positions during the machine index period, when dynamic forces in the horizontal plane might tend to displace them. In this case, with proper product design, where the parts are self-locating, the force due to gravity should be sufficient to hold the part until it is fastened or secured.

If assembly from above is not possible, it is probably wise to divide the assembly into subassemblies. For example, an exploded view of a British power plug is shown in Figure 8.15 and, in the assembly of this product, it would be relatively difficult to position and drive the two cord-grip screws from below. The remainder of the assembly (apart from the main holding screw) can be

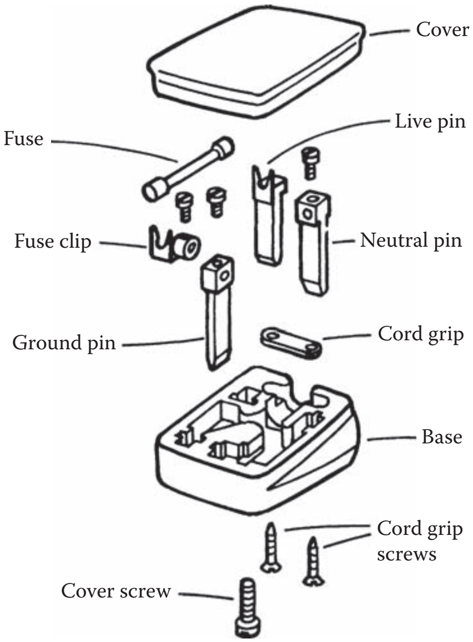


FIGURE 8.15 Assembly of three-pin power plug.

conveniently built into the base from above. In this example, the two screws, the cord grip, and the plug base could be treated as a subassembly dealt with prior to the main assembly machine.

It is always necessary in automatic assembly to have a base part on which the assembly can be built. This base part must have features that make it suitable for quick and accurate location on the work carrier. Figure 8.16a shows a base part for which a suitable work carrier would be difficult to design. In this case, if a force is applied at *A*, the part will rotate unless adequate clamping is provided. One method of ensuring that a base part is stable is to arrange that its center of gravity is contained within flat horizontal surfaces. For example, a small ledge machined into the part allows a simple and efficient work carrier to be designed (Figure 8.16b).

Location of the base part in the horizontal plane is often achieved by dowel pins mounted in the work carrier. To simplify the assembly of the base part onto the work carrier, the dowel pins can be tapered to provide guidance, as in the example shown in Figure 8.17.

8.9 DESIGN OF PARTS FOR FEEDING AND ORIENTING

Many types of parts feeders are used in automatic assembly (see Appendix D), and some of them have been studied in Chapter 3 and Chapter 4. Most feeders

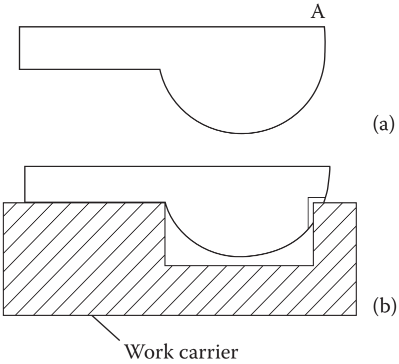


FIGURE 8.16 Design of base part for mounting on work carrier.

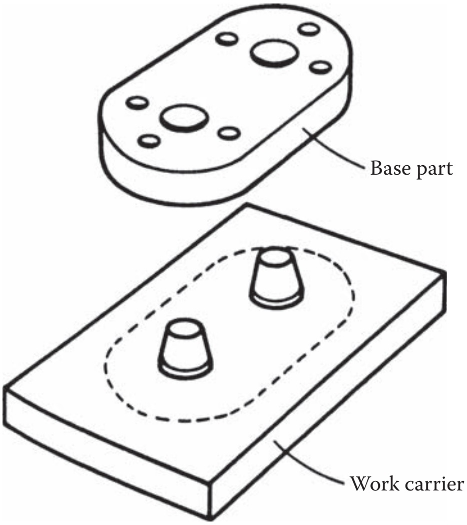
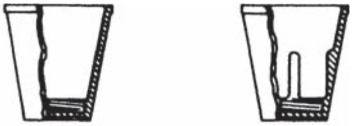


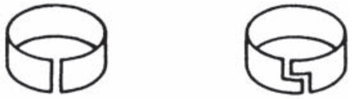
FIGURE 8.17 Use of tapered pegs to facilitate assembly.

are suitable for feeding only a very limited range of part shapes and are not generally relevant to discussions of the design of parts for feeding and orienting. The most versatile parts feeder is the vibratory-bowl feeder, and this section deals mainly with the aspects of the design of parts that will facilitate feeding and orienting in this type of feeder. Many of the points made, however, apply equally to other feeding devices. Three basic design principles can be enumerated:

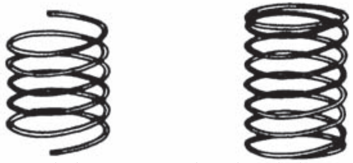
1. Avoid designing parts that will tangle, nest, or shingle.
2. Make the parts symmetrical.
3. If parts cannot be made symmetrical, avoid slight asymmetry or asymmetry resulting from small or nongeometrical features.



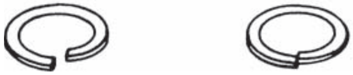
Parts will nest Rib in part will stop nesting



Straight slot will tangle Crank slot will not tangle



Open-ended spring will tangle Closed-ended spring will tangle only under pressure



Open spring-lock washer will tangle Closed spring-lock washer will tangle only under pressure

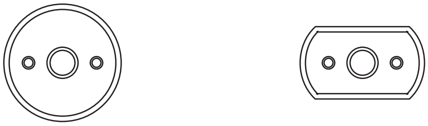
FIGURE 8.18 Examples of redesign to prevent nesting or tangling. (From Iredale, R., "Automatic Assembly — Components and Products," *Metalworking Production*, April 8, 1964. With permission.)

It can be almost impossible to separate, orient, and feed automatically parts that tend to tangle or nest when stored in bulk. Often, a small nonfunctional change in design will prevent this occurrence; some simple examples of this are illustrated in Figure 8.18.

Although the asymmetrical feature of a part might be exaggerated to facilitate orientation, an alternative approach is to deliberately add asymmetrical features for the purpose of orienting. The latter approach is more common, and some examples, given by Iredale [5], are reproduced in Figure 8.19. In each case, the features that require alignments are difficult to utilize in an orienting device, and so corresponding external features are added deliberately.

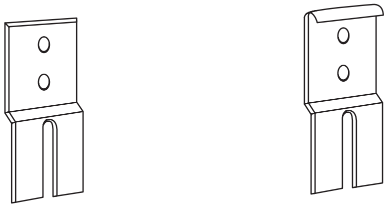
It will be noted that, in the coding systems shown in Figure. 8.4 and Figure 8.5, those parts with a high degree of symmetry all have codes representing parts that are easy to handle. There are, however, a wide range of codes representing parts that will probably be difficult to handle automatically; designers will require assistance with the problems these parts create.

Figure 8.20a shows a part that would be difficult to handle, and Figure 8.20b shows the redesigned part, which could be fed and oriented in a vibratory-bowl feeder at a high rate. The subtle change in design would not be obvious to the designer without the use of the coding system. Without it, it might not have occurred to the designer that the original part was difficult to handle automatically.



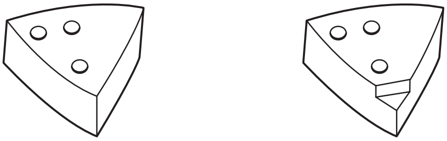
Difficult to orient with respect to small holes

Flats on the sides make it much easier to orient with respect to the small holes



No feature sufficiently significant for orientation

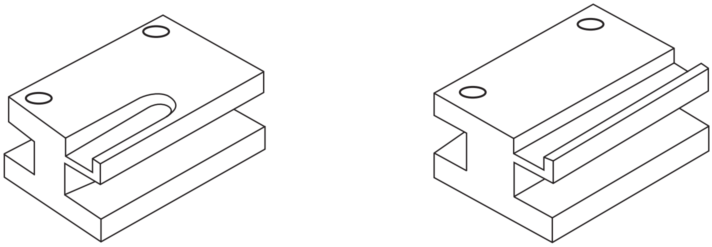
When correctly oriented will hang from rail



Triangular shape of part makes automatic hole orientation difficult

Nonfunctional shoulder permits proper orientation to be established in a vibratory feeder and maintained in transport rails

FIGURE 8.19 Provision of asymmetrical features to assist in orientation. (From Iredale, R., "Automatic Assembly — Components and Products," *Metalworking Production*, April 8, 1964. With permission.)



(a)
Very difficult to orient

(b)
Possible to orient

FIGURE 8.20 Less obvious example of a design change to simplify feeding and orienting.

It should be pointed out that, although the preceding discussion dealt specifically with automatic handling, parts that are easy to handle automatically are also easy to handle manually. A reduction in the time taken for an assembly worker to recognize the orientation of a part and then reorient it can result in considerable cost savings.

Clearly, with some parts, it will not be possible to make design changes that will enable them to be handled automatically; for example, very small parts or complicated shapes formed from thin strips are difficult to handle in an automatic environment. In these cases, it is sometimes possible to manufacture the parts on the assembly machine or to separate them from the strip at the moment of assembly. Operations such as spring winding or blanking out thin sections can be successfully introduced on assembly machines.

8.10 SUMMARY OF DESIGN RULES FOR HIGH-SPEED AUTOMATIC ASSEMBLY

The various points made in this discussion of parts and in the design of products for automatic assembly are summarized in the following subsections in the form of simple rules for the designer.

8.10.1 RULES FOR PRODUCT DESIGN

1. Minimize the number of parts.
2. Ensure that the product has a suitable base part on which to build the assembly.
3. Ensure that the base part has features that will enable it to be readily located in a stable position in the horizontal plane.
4. If possible, design the product so that it can be built up in layer fashion, each part being assembled from above and positively located so that there is no tendency for it to move under the action of horizontal forces during the machine index period.
5. Try to facilitate assembly by providing chamfers or tapers that will help to guide and position the parts in the correct position.
6. Avoid expensive and time-consuming fastening operations, such as screw fastening, soldering, and so on.

8.10.2 RULES FOR THE DESIGN OF PARTS

1. Avoid projections, holes, or slots that will cause tangling with identical parts when placed in bulk in the feeder. This may be achieved by arranging that the holes or slots are smaller than the projections.
2. Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency.

3. If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features that can be used to orient the parts.

8.11 PRODUCT DESIGN FOR ROBOT ASSEMBLY

As with product design for high-speed automatic assembly, one objective here is to provide the designer with a means of estimating the cost of assembling the product — but, in this case, using robots. However, several important design aspects will be affected by the choice of robot assembly system, a choice that in turn is affected by various production parameters such as production volume and the number of parts in the assembly. In Chapter 6, it was seen that three representative types of robot assembly systems can be considered namely:

1. Single-station with one robot arm
2. Single-station with two robot arms
3. Multistation with robots, special-purpose workheads, and manual assembly stations as appropriate

For a single-station system, those parts that require manual handling and assembly, and that must be inserted during the assembly cycle, present special problems. For reasons of safety, it is usually necessary to transfer the assembly to a location or fixture outside the working environment of the robot. This can be accomplished by having the robot place the assembly on a transfer device that carries the assembly to the manual station. After the manual operation has been completed, the assembly can be returned in a similar manner to within reach of the robot.

The use of special-purpose workheads for insertion or securing operations in a single-station robot system presents problems similar to those encountered for manual assembly stations. Two different situations can be encountered. In the first, the robot inserts or places the part without securing it immediately. This operation is followed by transfer of the assembly to an external workstation where the securing operation is carried out; a heavy press fit is an example. In the second situation, a special-purpose workhead is engineered to interact at the robot work fixture. This might take the form of equipment activated from the sides of, or underneath, the work fixture to carry out soldering, tab bending or twisting operations, spin riveting, etc., while the robot has to place and, if necessary, manipulate the part.

These major problems with single-station systems do not occur with the multistation system, where manual operations or special-purpose workheads can be assigned to individual stations as necessary. This illustrates why it is important to know the type of assembly system likely to be employed when the product is being designed.

In order to determine assembly costs, it is necessary to obtain estimates of the following:

1. The total cost of all the general-purpose equipment used in the system, including the cost of robots and any transfer devices and versatile grippers, all of which can be employed in the assembly of other products if necessary.
2. The total cost of all the special-purpose equipment and tooling, including special-purpose workheads, special fixtures, special robot tools or grippers, and special-purpose feeders; and special magazines, pallets, or part trays.
3. The average assembly cycle time, that is, the average time to produce a complete product or assembly.
4. The cost per assembly of the manual labor involved in machine supervision, loading feeders, magazines, pallets, or part trays, and the performance of any manual assembly tasks.

Classification systems and data bases have been developed for this purpose and were included in the original *Product Design for Assembly Handbook* [2]. The information presented in the handbook allowed these estimates to be made and included one classification and data chart for each of the three basic robot assembly systems. In these charts, insertion or other required operations were classified according to difficulty. For each classification, and depending on the difficulty of the operation, relative cost and time factors were given that could be used to estimate equipment costs and assembly times. These cost and time estimates were obtained by entering data from the appropriate chart onto a worksheet for each part insertion or separate operation.

Figure 8.21 to Figure 8.23 present the classification system and data for each type of robot assembly system. The selection of the appropriate row (first digit) depends on the direction of insertion, an important factor influencing the choice of robot because the SCARA-type assembly robot (Figure 5.41) can perform insertions only along the vertical axis. The selection of the appropriate column (second digit) depends on whether the part needs a special gripper and temporary clamping after insertion, and whether it tends to align itself during insertion. All these factors affect either the cost of the tooling required or the time for the insertion operation or both.

When the row and columns have been selected for a particular operation, the figures in the box allow estimates to be made of the robot cost, the gripper or tool cost, and the total time for the operation.

Let us suppose that a part to be inserted along a horizontal axis does not require a special gripper, requires temporary clamping, and is easy to align. For this operation, on a single-station one-arm robot system (Figure 8.21), the code would be 12. In this case, the relative robot cost AR is 1.5. This means that, if the basic capital cost of the installed standard four-degree-of-freedom robot (including all controls, sensors, etc., and capable of only vertical insertions) is

ROBOT ASSEMBLY DATA FOR A SINGLE-STATION ONE-ARM SYSTEM

AR	TP
AG	TG

TP - Relative affective basic operation time

AR - Relative robot cost

AG - Relative additional gripper or tool cost

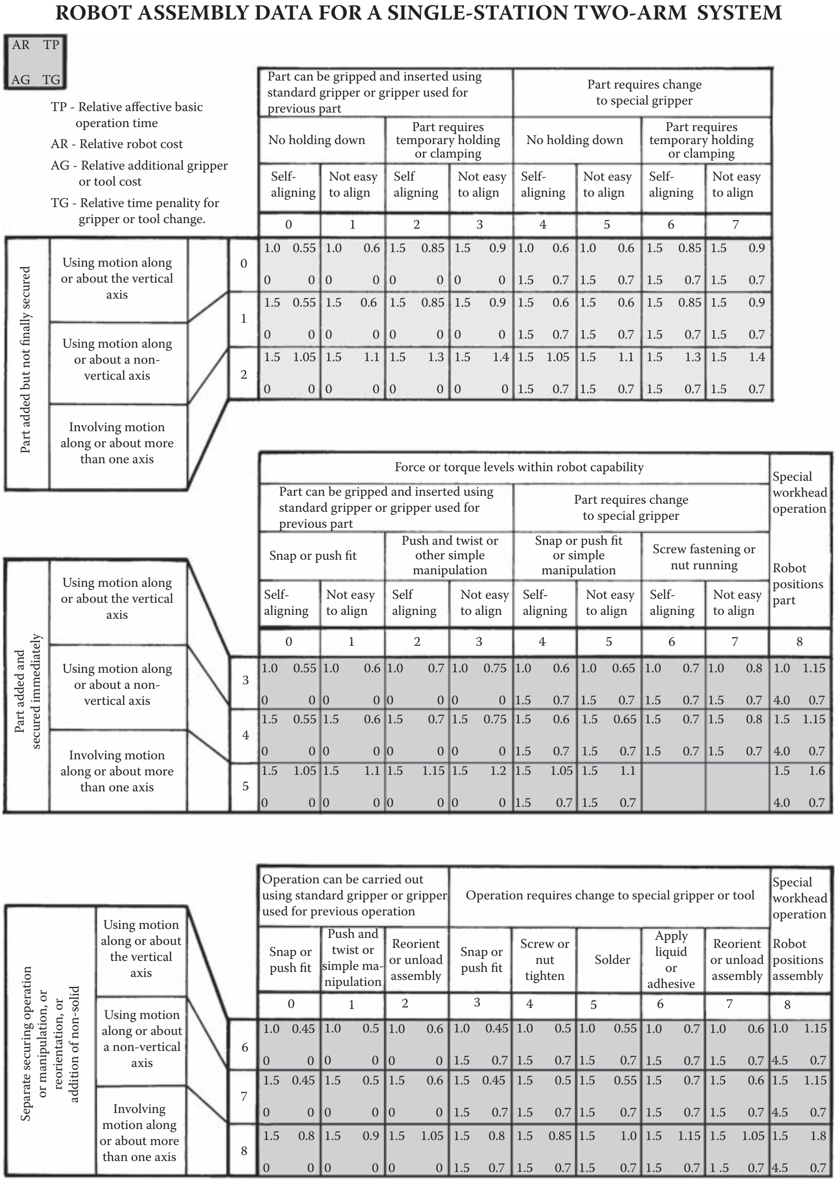
TG - Relative time penality for gripper or tool change.

			0	1	2	3	4	5	6	7
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper			
			No holding down		Part requires temporary holding or clamping		No holding down		Part requires temporary holding or clamping	
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0 1.0 0 0	1.0 1.07 0 0	1.0 1.0 1.0 0	1.0 1.07 1.0 0	1.0 1.0 1.5 2.1	1.0 1.07 1.5 2.1	1.0 1.0 2.5 2.1	1.0 1.07 2.5 2.1
	Using motion along or about a non-vertical axis	1	1.5 1.0 0 0	1.5 1.07 0 0	1.5 1.0 1.0 0	1.5 1.07 1.0 0	1.5 1.0 1.5 2.1	1.5 1.07 1.5 2.1	1.5 1.0 2.5 2.1	1.5 1.07 2.5 2.1
	Involving motion along or about more than one axis	2	1.5 1.8 0 0	1.5 1.9 0 0	1.5 1.8 1.0 0	1.5 1.9 1.0 0	1.5 1.8 1.5 2.1	1.5 1.9 1.5 2.1	1.5 1.8 2.5 2.1	1.5 1.9 2.5 2.1

			0	1	2	3	4	5	6	7	8
			Force or torque levels within robot capability								Special workhead operation
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper				
			Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulaion		Screw fastening or nut running		Robot positions part
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0 1.0 0 0	1.0 1.07 0 0	1.0 1.15 0 0	1.0 1.2 0 0	1.0 1.0 1.5 2.1	1.0 1.07 1.5 2.1	1.0 1.25 1.5 2.1	1.0 1.3 1.5 2.1	1.0 2.0 4.0 2.1
	Using motion along or about a non-vertical axis	4	1.5 1.0 0 0	1.5 1.07 0 0	1.5 1.15 0 0	1.5 1.2 0 0	1.5 1.0 1.5 2.1	1.5 1.07 1.5 2.1	1.5 1.25 1.5 2.1	1.5 1.3 1.5 2.1	1.5 2.0 4.0 2.1
	Involving motion along or about more than one axis	5	1.5 1.8 0 0	1.5 1.9 0 0	1.5 2.0 0 0	1.5 2.1 0 0	1.5 1.8 1.5 2.1	1.5 1.9 1.5 2.1			1.5 2.8 4.0 2.1

			0	1	2	3	4	5	6	7	8
			Operation can be carried out using standard gripper or gripper used for previous operation			Operation requires change to special gripper or tool					Special workhead operation
			Snap or push fit	Push and twist or simple manipulation	Reorient or unload assembly	Snap or push fit	Screw or nut tighten	Solder	Apply liquid or adhesive	Reorient or unload assembly	Robot positions assembly
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0 0.75 0 0	1.0 0.85 0 0	1.0 1.0 0 0	1.0 0.75 1.5 2.1	1.0 0.8 1.5 2.1	1.0 0.9 1.5 2.1	1.0 1.2 1.5 2.1	1.0 1.0 1.5 2.1	1.0 2.0 4.5 2.1
	Using motion along or about a non-vertical axis	7	1.5 0.75 0 0	1.5 0.85 0 0	1.5 1.0 0 0	1.5 0.75 1.5 2.1	1.5 0.8 1.5 2.1	1.5 0.9 1.5 2.1	1.5 1.2 1.5 2.1	1.5 1.0 1.5 2.1	1.5 2.0 4.5 2.1
	Involving motion along or about more than one axis	8	1.5 1.4 0 0	1.5 1.6 0 0	1.5 1.8 0 0	1.5 1.4 1.5 2.1	1.5 1.5 1.5 2.1	1.5 1.7 1.5 2.1	1.5 2.0 1.5 2.1	1.5 1.8 1 .5 2.1	1.5 3.2 4.5 2.1

FIGURE 8.21 Classification system and data base for a single-station one-arm robot assembly system. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)



ROBOT ASSEMBLY DATA FOR A SINGLE-STATION TWO-ARM SYSTEM

AR	TP
AG	TG

TP - Relative affective basic operation time
AR - Relative robot cost
AG - Relative additional gripper or tool cost
TG - Relative time penality for gripper or tool change.

			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper			
			No holding down		Part requires temporary holding or clamping		No holding down		Part requires temporary holding or clamping	
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align
			0	1	2	3	4	5	6	7
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0 0.55 0 0	1.0 0.6 0 0	1.5 0.85 0 0	1.5 0.9 0 0	1.0 0.6 1.5 0.7	1.0 0.6 1.5 0.7	1.5 0.85 1.5 0.7	1.5 0.9 1.5 0.7
	Using motion along or about a non-vertical axis	1	1.5 0.55 0 0	1.5 0.6 0 0	1.5 0.85 0 0	1.5 0.9 0 0	1.5 0.6 1.5 0.7	1.5 0.6 1.5 0.7	1.5 0.85 1.5 0.7	1.5 0.9 1.5 0.7
	Involving motion along or about more than one axis	2	1.5 1.05 0 0	1.5 1.1 0 0	1.5 1.3 0 0	1.5 1.4 0 0	1.5 1.05 1.5 0.7	1.5 1.1 1.5 0.7	1.5 1.3 1.5 0.7	1.5 1.4 1.5 0.7

			Force or torque levels within robot capability								Special workhead operation
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper				
			Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulation		Screw fastening or nut running		Robot positions part
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	
			0	1	2	3	4	5	6	7	8
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0 0.55 0 0	1.0 0.6 0 0	1.0 0.7 0 0	1.0 0.75 0 0	1.0 0.6 1.5 0.7	1.0 0.65 1.5 0.7	1.0 0.7 1.5 0.7	1.0 0.8 1.5 0.7	1.0 1.15 4.0 0.7
	Using motion along or about a non-vertical axis	4	1.5 0.55 0 0	1.5 0.6 0 0	1.5 0.7 0 0	1.5 0.75 0 0	1.5 0.6 1.5 0.7	1.5 0.65 1.5 0.7	1.5 0.7 1.5 0.7	1.5 0.8 1.5 0.7	1.5 1.15 4.0 0.7
	Involving motion along or about more than one axis	5	1.5 1.05 0 0	1.5 1.1 0 0	1.5 1.15 0 0	1.5 1.2 0 0	1.5 1.05 1.5 0.7	1.5 1.1 1.5 0.7			1.5 1.6 4.0 0.7

			Operation can be carried out using standard gripper or gripper used for previous operation			Operation requires change to special gripper or tool					Special workhead operation
			Snap or push fit	Push and twist or simple manipulation	Reorient or unload assembly	Snap or push fit	Screw or nut tighten	Solder	Apply liquid or adhesive	Reorient or unload assembly	Robot positions assembly
			0	1	2	3	4	5	6	7	8
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0 0.45 0 0	1.0 0.5 0 0	1.0 0.6 0 0	1.0 0.45 1.5 0.7	1.0 0.5 1.5 0.7	1.0 0.55 1.5 0.7	1.0 0.7 1.5 0.7	1.0 0.6 1.5 0.7	1.0 1.15 4.5 0.7
	Using motion along or about a non-vertical axis	7	1.5 0.45 0 0	1.5 0.5 0 0	1.5 0.6 0 0	1.5 0.45 1.5 0.7	1.5 0.5 1.5 0.7	1.5 0.55 1.5 0.7	1.5 0.7 1.5 0.7	1.5 0.6 1.5 0.7	1.5 1.15 4.5 0.7
	Involving motion along or about more than one axis	8	1.5 0.8 0 0	1.5 0.9 0 0	1.5 1.05 0 0	1.5 0.8 1.5 0.7	1.5 0.85 1.5 0.7	1.5 1.0 1.5 0.7	1.5 1.15 1.5 0.7	1.5 1.05 1 .5 0.7	1.5 1.8 4.5 0.7

FIGURE 8.22 Classification system and data base for a single-station two-arm robot assembly system. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

ROBOT ASSEMBLY DATA FOR A MULTI-STATION SYSTEM

AR	TP
AG	

TP - Relative affective basic operation time

AR - Relative robot cost

AG - Relative additional gripper or tool cost

			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper			
			No holding down		Part requires temporary holding or clamping		No holding down		Part requires temporary holding or clamping	
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align
			0	1	2	3	4	5	6	7
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0 1.0 0	1.0 1.1 0	1.0 1.05 1.0	1.0 1.15 1.0	1.0 1.0 0.5	1.0 1.1 0.5	1.0 1.05 1.5	1.0 1.15 1.5
	Using motion along or about a non-vertical axis	1	1.5 1.0 0	1.5 1.1 0	1.5 1.05 1.0	1.5 1.15 1.0	1.5 1.0 0.5	1.5 1.1 0.5	1.5 1.05 1.5	1.5 1.15 1.5
	Involving motion along or about more than one axis	2	1.5 1.8 0	1.5 1.9 0	1.5 1.85 1.0	1.5 1.95 1.0	1.5 1.8 0.5	1.5 1.9 0.5	1.5 1.85 1.5	1.5 1.95 1.5

			Force or torque levels within robot capability								Special workhead operation
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper				
			Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulaion		Screw fastening or nut running		
			Self-aligning	Not easy to align	Self aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	
			0	1	2	3	4	5	6	7	8
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0 1.0 0	1.0 1.1 0	1.0 1.1 0	1.0 1.2 0	1.0 1.0 0.5	1.0 1.1 0.5	1.0 1.25 0.5	1.0 1.3 0.5	0 1.0 4.0
	Using motion along or about a non-vertical axis	4	1.5 1.0 0	1.5 1.1 0	1.5 1.1 0	1.5 1.2 0	1.5 1.0 0.5	1.5 1.1 0.5	1.5 1.25 0.5	1.5 1.3 0.5	0 1.0 5.0
	Involving motion along or about more than one axis	5	1.5 1.8 0	1.5 1.9 0	1.5 2.0 0	1.5 2.0 0	1.5 1.8 0.5	1.5 1.9 0.5			0 1.5 6.0

			Operation can be carried out using standard gripper or gripper used for previous operation			Operation requires change to special gripper or tool					Special workhead operation
			Snap or push fit	Push and twist or simple manipulation	Reorient or unload assembly	Snap or push fit	Screw or nut tighten	Solder	Apply liquid or adhesive	Reorient or unload assembly	
			0	1	2	3	4	5	6	7	8
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0 0.75 0	1.0 0.85 0	1.0 1.0 0	1.0 0.75 0.5	1.0 0.8 0.5	1.0 0.9 0.5	1.0 1.2 0.5	1.0 1.0 0.5	0 1.0 3.5
	Using motion along or about a non-vertical axis	7	1.5 0.75 0	1.5 0.85 0	1.5 1.0 0	1.5 0.75 0.5	1.5 0.8 0.5	1.5 0.9 0.5	1.5 1.2 0.5	1.5 1.0 0.5	0 1.0 4.0
	Involving motion along or about more than one axis	8	1.5 1.4 0	1.5 1.6 0	1.5 1.8 0	1.5 1.4 0	1.5 1.5 0.5	1.5 1.7 0.5	1.5 2.0 0.5	1.5 1.8 0.5	0 1.5 4.5

FIGURE 8.23 Classification system and data base for a multistation assembly system. (From Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986. With permission.)

$60K, a cost of $90K is assumed. This figure allows for a more sophisticated robot able to perform operations from directions other than above. In other words, there is a cost penalty of $30K for the basic equipment in the system because the "standard robot" cannot perform the operation required.

The value of the relative additional gripper or tool cost AG is 1.0. Because the part needs temporary clamping, special tooling mounted on the work fixture would be required. Thus, if the standard tooling or gripper costs $5K, the additional tooling needed would represent a cost penalty of $5K in the form of special-purpose equipment.

The value of the relative basic operation time TP is 1.0. In this analysis method, the basis for time estimates is the average time taken by the robot to move approximately 0.5 m, grasp the part, return, and insert the part when the motion is simple and no insertion problems exist. For a typical assembly robot, this process might take 3 sec. If this figure is used in the present example, this is the basic time for the robot to complete the operation.

Finally, because the relative time penalty for gripper or tool change TG is zero, no additional time penalty is incurred, and the total operation time is 3 sec. In some cases such as that in which the part to be inserted is not completely oriented by the part-presentation device, a further time penalty must be added. In this case, the robot arm must perform the final orientation with the aid of a simple vision system, and an additional 2–3 sec must be added to the operation time.

In addition to the cost of the robot and the special tools or grippers, the costs of part presentation must be estimated. Before this can be accomplished it must be decided which part-presentation method will be used for each part. In practice, there are usually only two choices, namely (1) a special-purpose feeder or (2) a manually loaded magazine, pallet, or part tray.

The costs associated with part presentation can be divided into:

1. Labor costs, which include material handling (loading parts feeders or magazines), system tending (freeing jams in feeders, handling parts trays, etc.), and system changeover costs (changing of work fixture and feeders and magazines, and reprogramming of robots)
2. Equipment costs, including the depreciation of feeders, special fixtures special tooling, and magazines, pallets, or part trays

It can be assumed that the bulk material handling costs (i.e., dumping parts in bulk into feeder hoppers) are negligible compared to the cost of manually loading individual parts one by one into magazines, pallets, or part trays.

There are thus only three significant factors needed to estimate the cost of part presentation:

1. *Special-purpose feeders*. The cost of a special-purpose feeder, fully tooled and operating on the robot system, is assumed to be a minimum of $5K. The actual cost of a feeder for a particular part can be obtained

from the data presented earlier in this chapter, where feeding and orienting costs were considered in detail.

2. *Manually loaded magazines*. The cost of one set of special magazines, pallets, or part trays for one part type is assumed to be $1K. For larger parts, this may considerably underestimate the actual cost, and extra allowance should be made.
3. *Loading of magazines*. The time to hand-load one part into a magazine can be estimated from the part-handling time, obtained from the data in Chapter 7, plus 1 sec. Alternatively, a typical value of 4 sec may be used.

It can be seen that use of the classification systems and data base allows the total cost of equipment and the cost of any manual assembly work to be estimated, together with the assembly time for each part. These results provide the data necessary to predict assembly costs using each of the three robot assembly systems. A completed analysis is presented in Chapter 10, in which the cost of robot assembly, high-speed automatic assembly, and manual assembly are compared.

8.11.1 Summary of Design Rules for Robot Assembly

Many of the rules for product design for manual assembly and high-speed automatic assembly also apply to product design for robot assembly. However, when we weigh the suitability of a proposed design for robot assembly, we should carefully consider the need for any special-purpose equipment such as special grippers or special feeders. The cost of this equipment must be amortized over the total life volume of the product and, for the midrange volumes to which robot assembly might be applied, this can add considerably to the cost of assembly.

The following are some specific rules to follow during product design [2]:

1. Reduce part count; this is a major strategy for reducing assembly, manufacture, and overhead costs, irrespective of the assembly system to be used.
2. Include features such as leads, lips, and chamfers to make parts self-aligning in assembly. Because of the relatively poor repeatability of many robot manipulators compared to dedicated workhead mechanisms, this is a vitally important measure to ensure consistent fault-free part insertions.
3. Ensure that parts that are not secured immediately on insertion are self-locating in the assembly. For multistation robot assembly systems or one-arm single-station systems, this is an essential design rule. Holding down of unsecured parts cannot be carried out by a single robot arm, and so special fixturing is required, which must be activated by the robot controller. This adds significantly to special-purpose tooling and, hence, assembly costs. With a two-arm single-station system, one arm

can, in principle, hold down an unsecured part while the other continues the assembly and fastening processes. In practice, this requires one arm to change end-of-arm tooling to a hold-down device; the system then proceeds with 50% efficiency while one arm remains immobile.

4. Design parts so that they can all be gripped and inserted using the same robot gripper. One major cause of inefficiency with robot assembly systems arises from the need for gripper or tool changes. Even with rapid gripper or tool-change systems, each change in a special gripper and then back to the standard gripper is approximately equal to two assembly operations. Note that the use of screw fasteners always results in the need for tool changes because robot wrists can seldom rotate more than one revolution.
5. Design products so that they can be assembled in layer fashion from directly above (*Z*-axis assembly). This ensures that the simplest, least costly, and most reliable four-degree-of-freedom robot arms can accomplish the assembly tasks. It also simplifies the design of the special-purpose work fixture.
6. Avoid the need for reorienting the partial assembly or manipulating previously assembled parts. These operations increase the robot assembly cycle time without adding value to the assembly. Moreover, if the partial assembly has to be turned to a different resting aspect during the assembly process, this will usually result in increased work-fixture cost and the need to use a more expensive six-degree-of-freedom robot arm.
7. Design parts that can be easily handled from bulk. To achieve this goal, avoid parts that:
    Nest or tangle in bulk
    Are flexible
    Have thin or tapered edges that can overlap or “shingle” when moving along a conveyor of feed track
    Are delicate or fragile to the extent that recirculation in a feeder can cause damage
    Are sticky or magnetic so that a force comparable to the weight of the part is required for separation
    Are abrasive and will wear the surfaces of automatic handling systems
    Are light so that air resistance will create conveying problems (less than 1.5 N/m^3 or 0.01 lb/in^3.)
8. If parts are to be presented using automatic feeders, ensure that they can be oriented using simple tooling. Follow the rules for ease of part orientation discussed earlier. Note, however, that feeding and orienting at high speed is seldom necessary in robot assembly and that the main concern is that the features defining part orientation can be easily detected.

9. If parts are to be presented using automatic feeders, ensure that they can be delivered in an orientation from which they can be gripped and inserted without any manipulation. For example, avoid situations in which a part can be fed in only one orientation from which it must be turned over for insertion. This will require a six-degree-of-freedom robot and a special gripper or a special 180°-turn delivery track; both solutions lead to unnecessary cost increases.
10. If parts are to be presented in magazines or part trays, ensure that they have a stable resting aspect from which they can be gripped and inserted without any manipulation by the robot. It should be noted that, if the production conditions are appropriate, the use of robots holds advantages over the use of special-purpose workheads and that some design rules can be relaxed. For example, a robot can be programmed to acquire parts presented in an array, such as a pallet or part tray that has been loaded manually, thus avoiding many of the problems arising with automatic feeding from bulk. When making economic comparisons, however, the cost of manual loading of the magazines must be taken into account.

REFERENCES

1. Boothroyd, G. and Ho, C., Coding System for Small Parts for Automatic Handling, Society of Manufacturing Engineers, Paper ADR 76-13, Assemblex III Conference, Chicago, October 1976.
2. Boothroyd, G. and Dewhurst, P., *Product Design for Assembly Handbook*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1986.
3. Baldwin, S.P., How to Make Sure of Easy Assembly, *Tool and Manufacturing Engineering*, May 1966, p. 67.
4. Tipping, W.V., Component and Product Design for Mechanized Assembly, Conference on Assembly, Fastening and Joining Techniques and Equipment, Production Engineering Research Association, England, 1965.
5. Iredale, R., Automatic Assembly — Components and Products, *Metalworking Production*, April 8, 1964.

9 Printed-Circuit-Board Assembly

9.1 INTRODUCTION

Printed-circuit-board (PCB) assembly involves mainly the insertion and soldering of electrical *components* into PCBs. Component insertion is carried out manually or by high-speed, dedicated machinery. Additionally, robots are employed to perform insertions, mainly those that must otherwise be performed manually because of the *nonstandard* shapes of the components. For high production volumes, manufacturers may use a combination of automatic and manual insertion because odd-shaped or nonstandard components cannot be handled by the automatic insertion machines. It is desirable, however, to use automatic insertion machines wherever possible because they can operate much faster and with greater reliability than manual workers. For those PCBs manufactured in small batches and where the applications involve severe working environments, such as military applications, assembly may be performed entirely by hand.

At the end of this chapter, data and equations are presented that can be used to estimate the cost of component insertion and soldering either by dedicated automatic insertion machines, manual assembly workers, or robots.

9.2 TERMINOLOGY

For those not familiar with the terms used in PCB manufacture, a glossary of the terminology is included at the end of this chapter.

The term *insertion* is used to describe the process of placing a through-hole electrical *component* onto a PCB so that its leads pass through the correct holes in the board or of placing a *surface-mount* component onto the board in the required position. There are three methods of insertion: (1) dedicated automatic insertion machines, (2) manual assembly workers, including semiautomatic insertion, and (3) robots.

Automatic insertion of axial (VCD) components involves *preforming* the leads, inserting the component, and cutting and clinching the leads. Preforming and cut-and-clinch are done automatically as part of the insertion cycle and do not add to the cycle time or decrease the rate of insertion. Automatic insertion of DIPs does not involve lead forming or cutting.

With manual insertion and semiautomatic insertion, all the operations are performed manually in sequence. Thus, preforming before insertion and cut-and-clinch after insertion add to the total time for the insertion operation.

Robot insertion involves movement of the robot arm to the component, grasping the component, realigning it if necessary, moving it to the correct board location, and inserting it. If the component feeders or presenters cannot completely orient the component, robot insertion will include final realignment and will increase the cycle time. As with manual assembly, preforming and cut-and-clinch are usually done separately.

Robots are generally used only to insert nonstandard components that otherwise would have been inserted manually. Nonstandard or odd-form components are those large or small or odd-shaped components that cannot be inserted by special-purpose machinery.

Before introducing the cost analysis for PCB assembly, the complete assembly procedure will be described. The following section explains the various steps that can be included in a PCB assembly process; these steps are automatic, manual, and robotic insertion of components.

9.3 ASSEMBLY PROCESS FOR PCBS

Figure 9.1 shows all the possible steps in an assembly process for PCBs [1]. The figure includes that portion of PCB manufacture in which component insertions are carried out. Component presentation, repair for faulty insertions, and *touch-up* for faulty soldering are also included. Steps that do not directly involve the addition of components to the board, however, such as board preparation, where

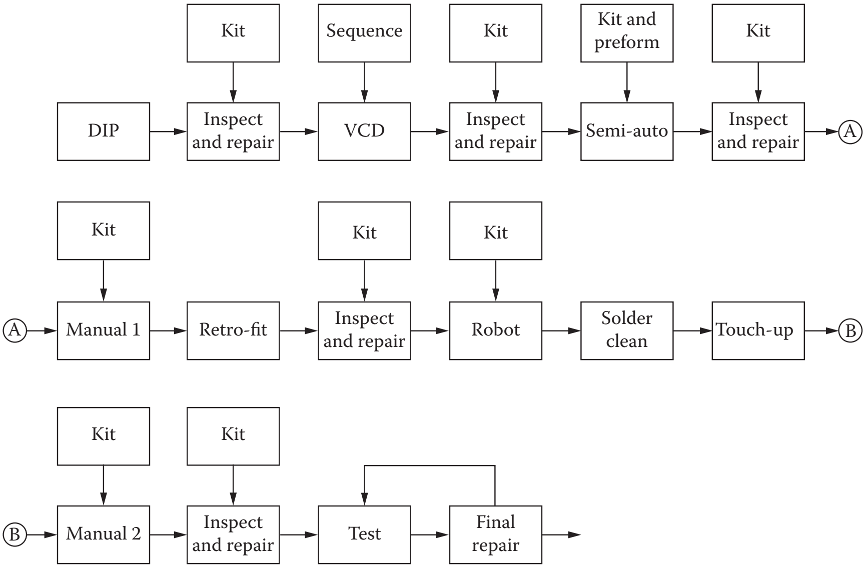


FIGURE 9.1 Typical assembly process for PCBs. (From John, J. and Boothroyd, G., Economics of Printed Circuit Board Assembly, Report 6, Economic Application of Assembly Robots Project, University of Massachusetts, Amherst, MA, April 1985. With permission.)

boards are given identification codes; board cut, where a series of identical boards is cut from a larger panel; and final test, where functional testing of the board is done, are not included. Boards move through the steps as indicated by the horizontal lines on the figure. The vertical lines indicate the flow of components from inventory to the insertion stations.

In order to minimize handling and processing time, small boards are sometimes processed in the form of larger panels which, after the components are inserted and soldered, are separated into the individual boards. Alternatively, several separate boards can be mounted in one fixture to be processed together.

The first block in the assembly process shown in Figure 9.1 indicates DIP. This refers to the automatic insertion of dual in-line package (DIP) components and includes all integrated circuit chips and chip sockets. The term *dual in-line package* refers to the two parallel rows of leads projecting from the sides of the package (Figure 9.2). Typically, DIPs have 4–40 leads; DIPs with more than 40 leads are infrequently used. The lead span, which is the distance between the two rows of leads, is standardized at 0.3, 0.4, or 0.6 in.

At the DIP station, components are inserted with an automatic DIP inserter (Figure 9.3). Automatic insertion is carried out at high rates, approximately 2800–4500/h or one component every 0.80–1.29 sec. The DIP leads are inserted through predrilled holes in the board and are cut and clinched below the board (Figure 9.4). The automatic insertion head moves only in the vertical direction while the board is positioned below it on an x-y table that can also rotate. High-performance DIP insertion machines can insert DIPs having any of the three standard lead spans with no tooling change, but base models can handle only 0.3-in. lead spans and 6–20-lead DIPs. To accommodate 2- and 4-lead DIPs, a special insertion head must be employed at additional cost. To check for electrical *faults*, a component verifier may be employed that will stop the machine if certain preprogrammed electrical characteristics are not met.

DIP components are purchased from component manufacturers in long tubes called *channels*, in which the components are preoriented and stacked end to end. The channels are loaded onto the DIP inserting machine. Usually, one channel is used for each DIP type on the board but, if large numbers of one type are used, more channels can be assigned to the same component. A *magazine* refers to a group of channels, usually about 15. If a high component mix is required, additional magazines can be added to the machine. The machine size and speed restricts the number of magazines. The insertion cycle time is longer when the channel is farther from the insertion head. Channels can be changed by an operator as the machine is running, which eliminates downtime caused by empty channels.

After DIP insertion, the next block in the assembly process shown in Figure 9.1 indicates inspect and repair. This is an inspection of the partially assembled board by the inspector who is looking for faults that can be detected visually, such as broken or bent leads or components inserted into the wrong holes. Components are either repaired and reinserted or discarded and replaced. Workers have available at each repair station all the components inserted at the previous insertion station, so that any component may be replaced. Inspect-and-repair

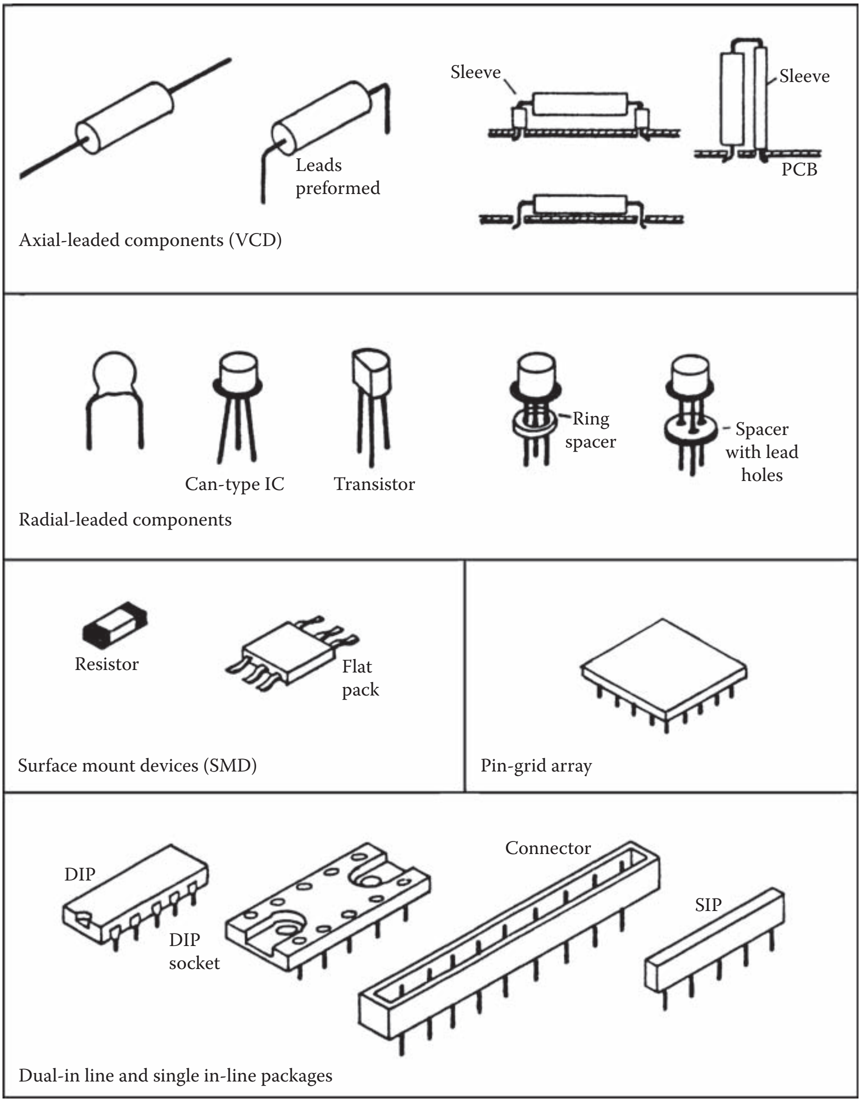


FIGURE 9.2 Various electronic components (not to scale).

stations can follow each insertion station. However, workers can never detect all the faults, and those that go undetected will inevitably have to be detected and corrected later in the manufacturing process.

The second insertion station in the assembly process is VCD insertion. This refers to the automatic insertion of *axial-lead components* (Figure 9.2), also called VCD (variable center distance) components. These include resistors, capacitors, and diodes within the size limitations of the insertion head. Axial-lead

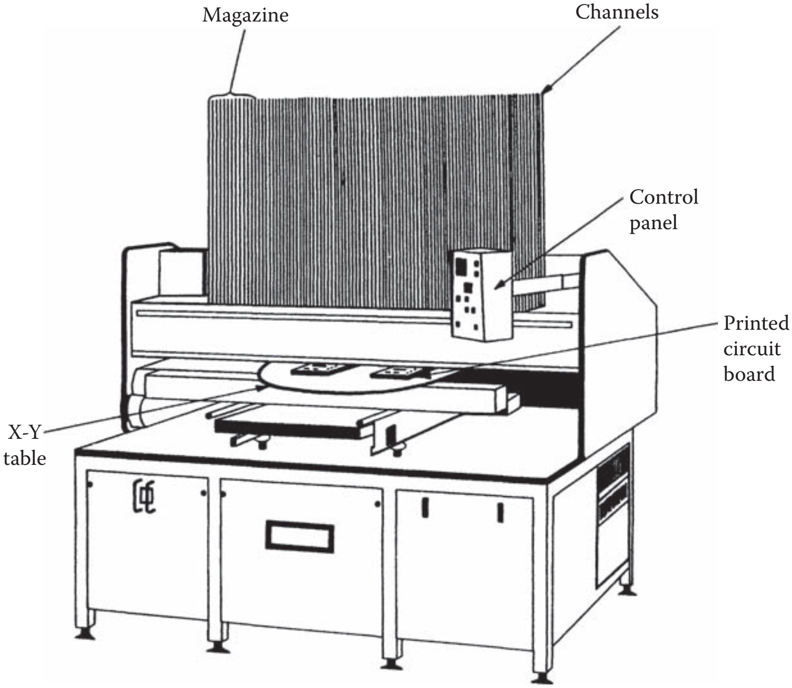


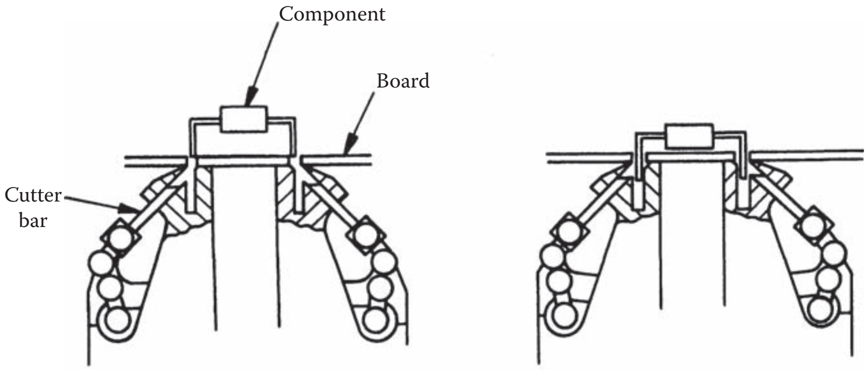
FIGURE 9.3 Automatic DIP insertion machine.

components must usually have their leads bent at right angles prior to insertion, and the final lead span (called *center distance*) is variable.

At this second station, axial-lead components are inserted with an automatic axial-lead inserter (Figure 9.5). Axial-lead components are inserted at rates of approximately 9,500 to 32,000 components/h or one component every 0.11–0.38 sec. Rates of 32,000/h can be achieved only with a dual-head insertion machine, a machine that inserts components into two identical boards simultaneously. Obviously, single-head axial-lead insertion machines work at half the rate of dual-head machines. The rates are higher than those for automatic DIP insertion because components are fed on a *spool* in the correct sequence for insertion (Figure 9.6) and do not have to be moved as far to reach the insertion head. Spools can hold large numbers of components and only have to be changed infrequently.

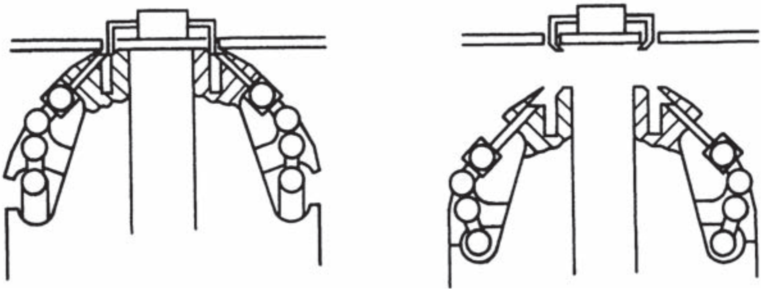
Automatic axial-lead insertion proceeds as follows:

1. Components are stored on a spool in the correct order for insertion (this is accomplished by the automatic component sequencer described in the following text).
2. The spool is loaded manually onto the axial-lead inserter.



Component in position for insertion

Component inserted with leads extending into cut and clinch mechanism



Cutter bar cuts and clinches leads

Cut and clinch mechanism returns to rest position

FIGURE 9.4 Cut-and-clinch sequence.

3. During the automatic insertion cycle, the leads are automatically cut to remove the component from the tape; then they are bent at right angles to the correct center distance, and the component is positioned with the leads passing through the board.
4. Finally, the leads are cut and clinched below the board (Figure 9.4).

As indicated in Figure 9.1, axial-lead components are first mounted on a spool using a component *sequencer*. This machine (Figure 9.7) arranges the components on a tape spool in the correct sequence for insertion. Axial-lead components are purchased on spools, with one component type on each spool. Spools are loaded manually onto the sequencer for every type of component on the board and, from these, a master spool is created.

A component sequencer can handle components at a rate of approximately 10,000–25,000/h or one component every 0.14–0.36 sec. Component leads are

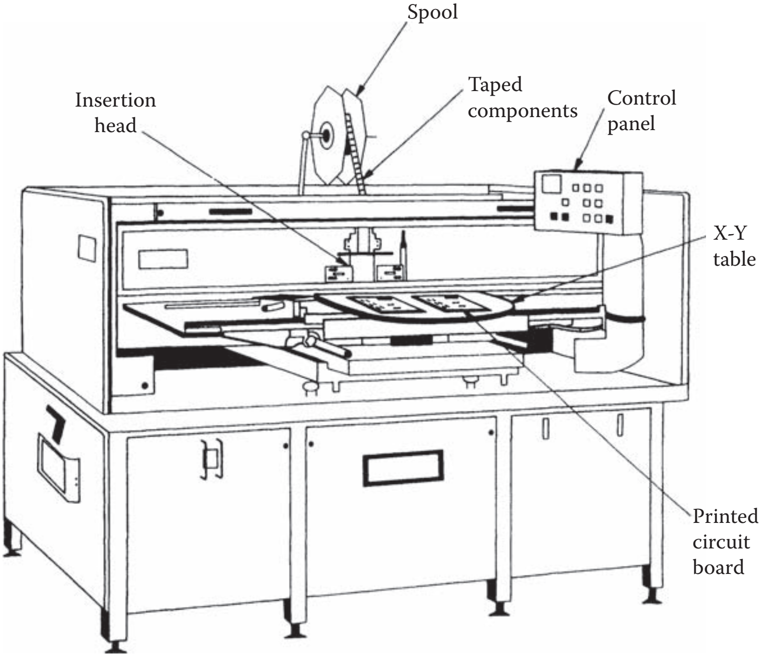


FIGURE 9.5 Automatic axial-lead insertion machine.

automatically cut to remove the components from their individual tapes in the correct order for insertion. Components are then retaped and rolled onto the master spool. Master spools are made off-line and in advance of the component insertion process.

A *module* for a sequencer is a group of dispensing spools, usually about 20 in number. If a larger component mix is needed, additional modules can be added to the sequencer up to a maximum of about 240 dispensing spools, with the limit being imposed by the physical size of the machine. To check for faulty components or a component out of order, a component verifier can be added to the sequencer.

These last two processes, automatic axial-lead component insertion and sequencing, may be combined and carried out on one machine. Such a machine, about twice as large as a conventional automatic insertion machine, eliminates the need for *kitting* and reduces setup time by bringing inventory to the assembly line. Since components are stored at the assembly line, different batches can be run, both large and small, by simply writing a new program for each batch.

In addition to these automatic insertion processes, PCB manufacturers may include stations for the automatic insertion of *radial-lead components* and single in-line package (SIP) components (Figure 9.2). Automatic insertion machines for radial-lead components are similar to automatic axial-lead component insertion machines, and automatic SIP inserters are similar to automatic DIP inserters.

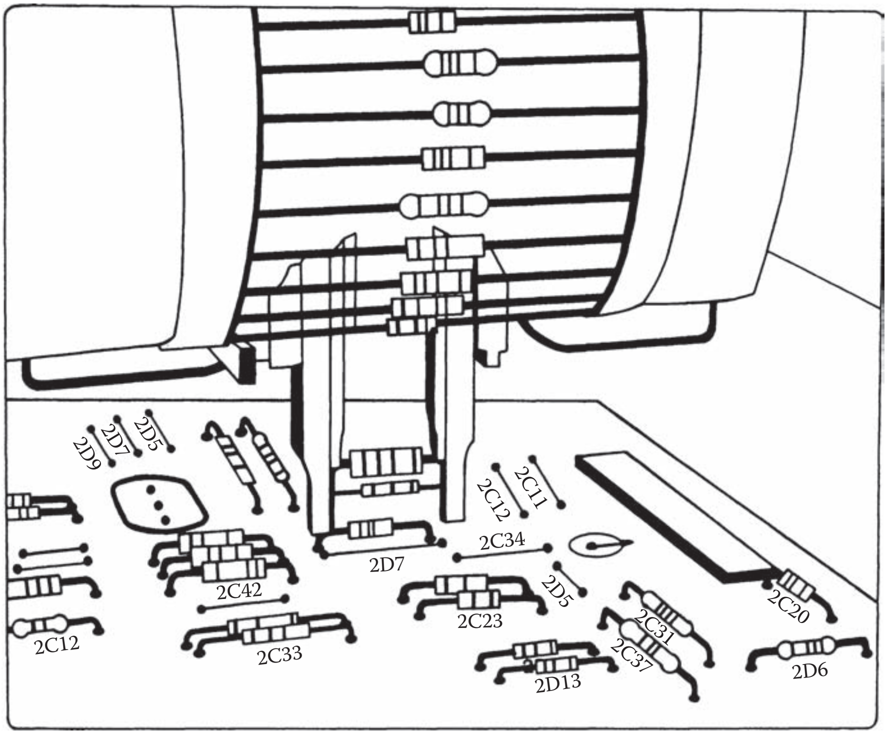


FIGURE 9.6 Axial-lead components on tape at insertion head.

Some DIP insertion machines have as an option the ability to insert SIP components using an additional insertion head. Also, the first three stations in Figure 9.1 may each include duplicate machines if the number of components per board is high.

The next block in the PCB assembly process shown in Figure 9.1 indicates semiauto. This refers to semiautomatic component insertion, i.e., machine-assisted manual insertion. Inserted at this station are all DIP and axial-lead components that cannot be machine-inserted because of either their size or their location on the board. Also inserted are radial-lead components, SIPs, and some connectors. Wherever possible in high-volume assembly, semiautomatic insertion is used instead of manual insertion since it can reduce insertion times by 80%.

A semiautomatic insertion machine (Figure 9.8) automatically presents the correct component to the operator and indicates, by use of a light beam, the correct location and orientation for the component on the board. The component is then inserted by hand, with the leads sometimes being automatically cut and clinched. Components are inserted in this way at rates of approximately one component every 5 sec. All components must have their leads preformed to the correct dimensions for insertion prior to presentation to the operator. Typically,

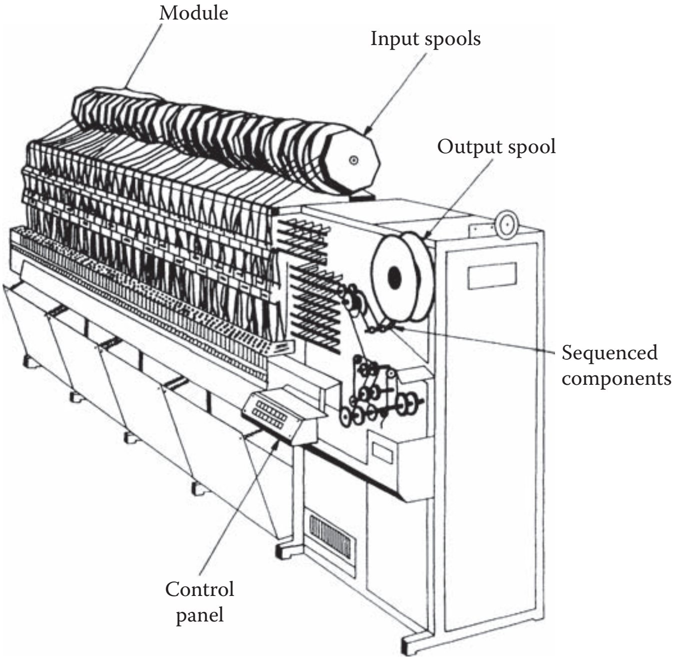


FIGURE 9.7 Automatic axial-lead sequencing machine.

components are stored in a rotating tray. After receiving a signal from the operator, the tray rotates so that only the section containing correct components is presented. The light beam (which can be located either above or below the board) illuminates the holes for the insertion and uses a symbol to indicate component polarity.

There are two manual assembly stations, Manual 1 and Manual 2, shown in the PCB assembly process in Figure 9.1. One station is before, and the other after, *wave-soldering*. The two stations are sometimes needed because some components cannot withstand the high temperatures of wave-soldering. Both are manual insertion stations, which may involve the use of special hand tools to facilitate the handling and insertion of certain components. Typically, manual assembly accounts for a high proportion of total assembly time, even when a relatively small number of manually assembled components are involved.

At the first manual assembly station, large nonstandard components are inserted. They are inserted manually because the part trays used in semiautomatic machines cannot accommodate many of these parts on account of their large size. If a particular manufacturer does not use a semiautomatic machine, all the components that would have been inserted using this machine will be inserted manually. Also, components assembled mechanically (i.e., secured with screws or bolts) that are to be wave-soldered are assembled here.

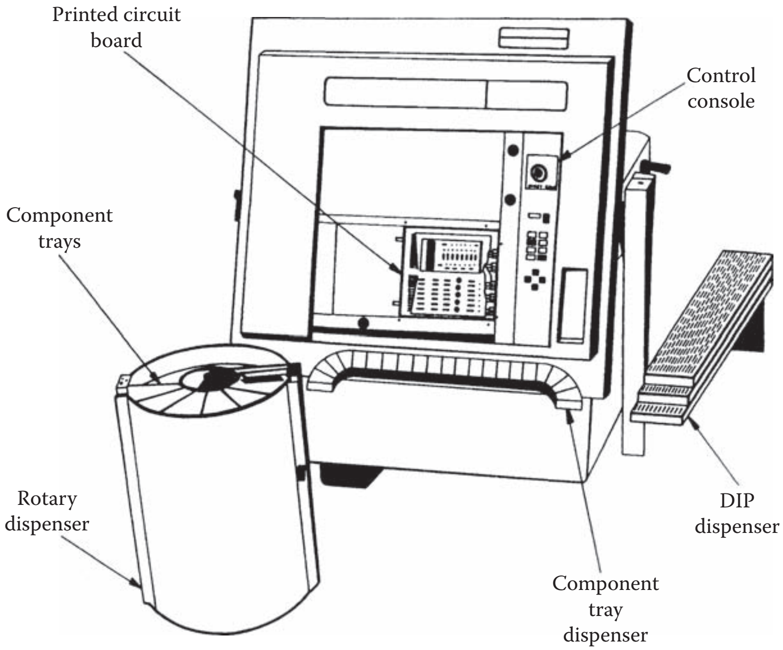


FIGURE 9.8 Semiautomatic insertion machine.

After the first manual assembly station is a block indicating retrofit (Figure 9.1). Assembly here is also manual but involves only engineering change order (ECO) wires or jumper wires. These wires are cut to the required length from spools, and the ends are stripped and *tinned*. One end of the wire is soldered to a component lead on top of the board or is inserted through the board; the wire is routed around the board and *cemented* down at various points. Finally, the other end is soldered to a component lead or inserted into the board. These ECOs are often needed to satisfy certain customer options and are sometimes needed because it is difficult to fit the entire etched circuit on a board without having to cross paths at some point. An alternative is to use a multilayer circuit board (one with two or more circuits printed on it with insulating material separating the circuits).

An assembly station for robotic insertion is included in the assembly process (Figure 9.1) and occurs after retrofit in the flow diagram. At this station, robotic insertion of nonstandard components using a robot may be performed. Robot insertion is used mainly to reduce the amount of manual labor involved in PCB assembly.

Solder-clean, the next station in the assembly process (Figure 9.1), refers to wave-soldering of the component leads on the underside or solderside of the board and the removal of excess flux applied to the solderside of the board prior to soldering. A conveyor carries the PCB assembly over a rounded crest or wave of solder so that the board impinges against the wave in passing. The purpose of applying a flux, usually an organic rosin type, is to remove from the board oxides that inhibit solderability. Cleaning is subsequently done to remove excess flux, which could cause corrosion and/or contamination.

The time taken for wave-soldering and cleaning one board or, in the case of small boards, one panel or fixture, depends on the conveyor speed, with conveyor speed adjustment up to 20 fpm. Typically, conveyor speeds are near 10 fpm, which yields a time of approximately 2 min for a board, panel, or fixture to pass through the wave-soldering and cleaning station. However, conveyor speeds are selected to yield specific solder contact times, which are usually about 3 sec.

Immediately following solder and clean is *touch-up*. Touch-up is cleaning the solderside of the board to remove excess solder. This is necessary because of the tendency of the solder to icicle and bridge, which can cause short circuits in the electrical layout. Icicling and bridging are more prevalent on closely packed boards.

At the second manual assembly station (often referred to as “final assembly”), all the remaining components are inserted (Figure 9.1). These include components that cannot be wave-soldered because of their sensitivity to heat. Also, components that are secured mechanically are installed here. These include handles, some large electrolytic capacitors, connectors, and power *transistors*, which are secured with screws or bolts and nuts. Lastly, some components, such as diodes and resistors, usually with axial leads, are soldered on the top of the board to the leads of other components. These operations, if necessary, are a type of engineering change order, and there is a need to reduce the number of components inserted at this station because of the greater time involved with hand-soldering compared to wave-soldering.

9.4 SMD TECHNOLOGY

The preceding discussion has dealt only with PCBs having through-hole components where the component leads pass through the board. However, the surface-mount devices (SMDs) are increasingly employed. These components have pads or leads soldered to corresponding areas on the surface of the board. Assembly of an SMD involves positioning the component on the board, which has previously had the solder paste applied. When all the SMDs have been positioned, the board is *reflow-soldered*. This involves heating the solder paste until it flows into a uniform solder layer, which permanently affixes the SMD pads or leads to the board. Passive SMD components such as resistors and capacitors can also be added to the underside of the board using adhesive. Soldering them takes place during wave-soldering.

SMDs include simple resistors in the form of a small rectangular prism and a variety of larger components, such as flat packs (Figure 9.2). These devices can be mounted on either side of the board and are usually interspersed with through-hole components.

Also, there are many variations on the PCB assembly sequence described here. In particular, the use of robots is increasing and, for high-volume production,

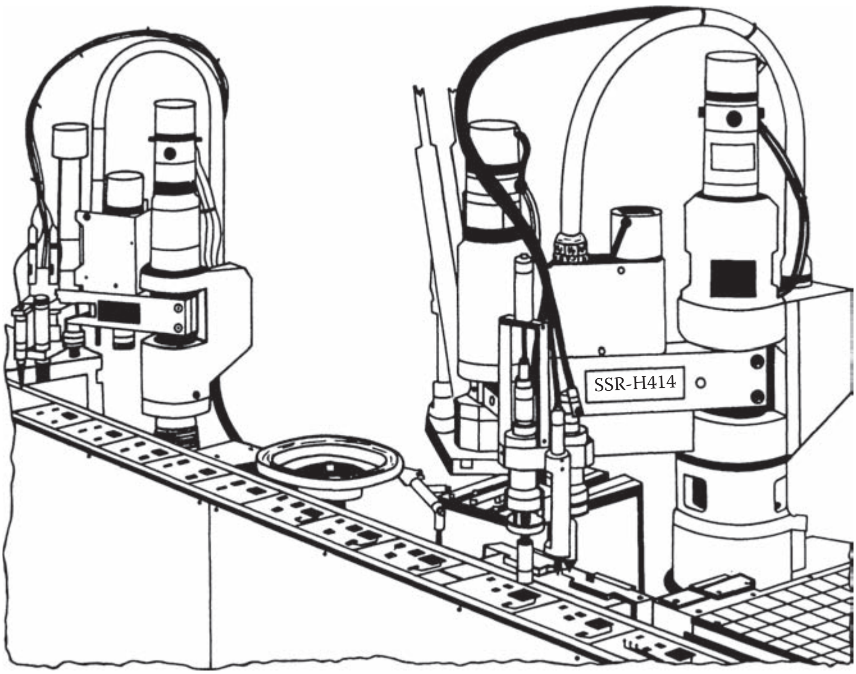


FIGURE 9.9 Robot assembly of PCBs.

these can be arranged in assembly-line fashion, as illustrated in Figure 9.9. With such an arrangement, the components are usually presented in standardized *pallets*, roughly oriented. The robot must then provide the final orientation prior to insertion and, for this purpose, vision systems might be employed. Alternatively, some components or mechanical parts are delivered to a station using standard feeding and orienting techniques. The robot then acquires the preoriented component or part at the station.

It should be realized that PCB manufacture is a rapidly developing process. New PCB designs, new component packaging, and new assembly techniques are continually being introduced. Manufacturers constantly strive to achieve higher component densities, which makes assembly increasingly difficult.

9.5 ESTIMATION OF PCB ASSEMBLY COSTS

The materials necessary for an estimation of PCB assembly costs are presented at the end of this section [2]. Data bases giving the times for manual insertion are included, and a worksheet is provided to assist in tabulating the results. Components and operations are entered on the worksheet in assembly order, one line for each basic type of component or operation.

The time for manual insertion, obtained from the data base, is entered on the worksheet and then multiplied by the operator rate to give the insertion cost.

After adding per-component allowances for *rework* costs, the total operation cost is entered.

For automatic or robot insertion, the cost is obtained directly from the data base and then adjusted for programming, setup, and rework.

For mechanical parts, the manual assembly times and costs can be obtained from Chapter 7. When all the operations have been entered, the total cost is obtained by summing the figures in the cost column.

Figure 9.10 shows, by way of example, a completed worksheet for a PCB assembly taken from a microcomputer. Such an assembly is commonly referred to as a "logic board." This particular board contains 69 DIPs, 1 DIP socket, 16 axial components, and 32 radial components. In addition, two parts are attached mechanically, requiring 11 screws, nuts, and washers. It is assumed that the DIPs, radials, and axials are autoinserted and that the remaining components or parts are manually inserted or assembled except for one DIP, which is assembled into the corresponding DIP socket after wave solder. The completed worksheet for this example board gives a total estimated assembly cost of $3.48. Consideration of avoidable costs indicates that elimination of the 11 fasteners would save 48 cents, a surprisingly high figure for a board with only one nonelectrical component, namely, the end plate.

The operations costs for the automatic insertion processes include the cost of rework, which amounts to a total of 46.1 cents — clearly a significant item.

In estimating the cost of wave solder, it was assumed that two boards would be processed together. However, the resulting use of 75 cents is a significant item and, in practice, should be examined closely for accuracy.

Finally, it was assumed in this analysis that the manufacturer would have an automatic machine available for the insertion of the 32 radial components. It is interesting to note that if these components were to be inserted manually, an additional expense of $2.19 would be incurred, increasing the total cost of assembly by 63%.

9.6 WORKSHEET AND DATABASE FOR PCB ASSEMBLY COST ANALYSIS

9.6.1 INSTRUCTIONS

1. For soldered components, assemblies, or operations, use the data base provided here. For all other parts, components, or operations, use the manual assembly data from Chapter 7.
2. Record the data on the worksheet in the following order of assembly:
   a. Load PCB into fixture.
   b. Insert all wave-soldered components.
      i autoinserted
      ii robot-inserted
      iii manually inserted

Name of PCB color card	Operator rate $W_a = 0.6$ cents/s		Batch size $B_s = 1{,}000$	Number of setups $N_{set} = 10$		No. of boards/panel $N_b = 2l$
Name of item	**No. of pins or leads N_l**	**Repeat count R_p**	**Manual op. time, s t_a**	**Total op. cost, cents C_{op}**	**Minimum parts N_m**	**Description**
Circuit board		1	4.0	2.4	1	Place in fixture
DIP	20	11		19.9		Auto. insert
DIP	14	56		82.9		Auto. insert
Axial	2	16		24.3		Auto. insert
Radial	2	32		47.0		Auto. insert
DIP socket	24	1	18.0	13.0		Manual insert
DIP	40	1	26.0	19.2		Manual insert
Screw		2	15.6	9.4	0	Add
Coaxial connector	3	1	8.0	5.1		Manual insert
Display connector	9	1	8.0	5.6		Manual insert
Star washer		2	17.4	10.4	0	Add and hold
Nut		2	8.8	5.3	0	Add and screw
End plate		1	4.5	2.7	1	Add
Lock washer		2	9.4	5.6	0	Add
Hexagonal nut		2	19.8	11.9	0	Add and screw
Screw		1	9.8	5.9	0	Add and screw
Wave solder		1		75.0		Wave solder
DIP	24	1	4.0	2.4	1	Add and snap fit
			Total	348		

FIGURE 9.10 Completed worksheet for sample PCB assembly.

c. Wave-solder.
d. Insert and solder all manually soldered components:
    i autoinserted
    ii robot-inserted
    iii manually inserted
e. Insert and secure all remaining nonsoldered components.

If parts and mechanical fasteners are associated with any soldered components, list them with the appropriate component.

9.7 PCB ASSEMBLY — EQUATIONS AND DATA FOR TOTAL OPERATION COST

Name of PCB	**Operator rate W_a =__ cents/s**		**Batch size B_s = __**	**Number of setups N_{set} = __**		**No. of boards/panel N_b = __**
Name of item	**No. of pins or leads N_l**	**Repeat count R_p**	**Manual op. time, s t_a**	**Total op. cost, cents C_{op}**	**Minimum parts N_m**	**Description**
			Total			

Note: t_a is inappropriate for auto or robot insertion unless hand solder is carried out; $N_{\min}$ is inappropriate for soldered electronic components.

PCB Assembly Data for Manual Operations

Insertion of Components			
Component types	**Operations**		**Time, s**
Axials (VCDs)	Bend leads, insert, cut and clinch leads		19
Radials or can-type ICs	Insert component, cut and clinch leads	Basic time	10
		Additional time per lead	1.8
SIP/SIP sockets or connectors	Insert component	≤80 leads	8
		>80 leads	10
Posts, DIP/DIP sockets, pin-grid arrays or odd-form components	Insert component	Basic time	6
		Additional time per lead or post	0.5
SMDs	Add and solder using special fixture or tool		10

Other manual operations		
Part	**Operation**	**Time, s**
Sleeve	Cut one sleeve, add to a lead	15
Jump wire (ECO)	Cut, strip and tin ends; insert and solder	60
Heat sink	Add to transistor	25
Lead or post	Hand-solder one lead or post	6

Source: Adapted from Boothroyd, G. and Shinohara, T., "Component Insertion Times for Electronics Assembly," International Journal of Advanced Manufacturing Technology, 1(5), 1986, p. 3.

9.7.1 MANUAL

$$C_{\text{op}} = t_a W_a + R_p C_{\text{rw}} M_f \text{ cents}$$

9.7.2 AUTOINSERTION MACHINE

$$C_{\text{op}} = R_p(C_{\text{ai}} + C_{\text{ap}}/B_s + C_{\text{rw}} A_f) + N_{\text{set}}\, C_{\text{as}}/B_s \text{ cents}$$

9.7.3 ROBOT INSERTION MACHINE

$$C_{\text{op}} = R_p(C_{\text{ri}} + C_{\text{rp}}/B_s + C_{\text{rw}} R_f) + N_{\text{set}}\, C_{\text{rs}}/B_s \text{ cents}$$

Insertion costs per component (cents)		
Component types	**Auto., C_{ai}**	**Robot, C_{ri}**
Axial (VCD)	1.2*	5
Radial	1.2*	5
SIP/SIP socket	0.8	5
DIP/DIP socket	0.8	5
Connector	1.0	5
Small SMD (2 connections)	0.2	5
Large SMD (>2 connections)	1.0	5

Associated costs (dollars)	
Wave or reflow solder**	1.5

[a] Includes cost of sequencing.

[b] If several boards are contained in one panel or secured in a single fixture, divide this figure by N_b, the number of boards per panel or fixture, in order to obtain the cost of wave or reflow solder per board. This figure also includes the time to place the boards or panel in the soldering fixture.

where

A_f = average number of faults requiring rework for each auto insertion (0.002)
B_s = total batch size
C_{ai} = cost of autoinsertion (obtained from data base)
C_{ap} = programming cost per component for autoinsertion machine (150 cents)
C_{as} = setup cost per component type for autoinsertion machine (150 cents)
C_c = cost of replacement component when rework is needed
C_{ri} = cost of robot insertion (obtained from data base)
C_{rp} = programming cost per component for robot system (150 cents)
C_{rs} = set up cost per component type for robot system (150 cents)
C_{rw} = $T_{\mathrm{rf}} N_\ell W_a + C_c$ and is the average rework cost per faulty component (cents)
M_f = average number of faults requiring rework for each manual insertion (0.005)
N_ℓ = number of leads or posts on one component
N_{set} = estimated number of setups per batch
R_f = average number of faults requiring rework for each robot insertion (0.002)
R_p = number of components
t_a = total time for all manual operations (calculated from data base figures)
T_{rf} = average estimated time to rework one component fault per lead or post (30 sec)
W_a = rate for manual operations, cents/sec

9.8 GLOSSARY OF TERMS

The following is a brief description of some of the terminology used in this chapter. The physical configurations of some electrical components, the manual assembly operations, and some terms pertaining to automatic insertion equipment are described.

Axial-leaded component: Electrical component of cylindrical shape with two leads exiting from opposite ends of the component in line with its axis (Figure 9.2). The component is sometimes called a VCD (variable center distance). The most common axial-leaded components are resistors, capacitators, and diodes.

Can-type IC: A cylindrical integrated circuit, packaged so that the leads form a circular pattern (Figure 9.2). This multileaded radial component can have 3–12 leads.

Cement: Because of the requirements for ruggedness placed on some PCBs, components can be cemented to the board to reduce the effects of vibrations. This sometimes requires that the component leads be bent prior to cementing.

Center distance: Distance between leads when formed for insertion. This term applies to two-leaded components and DIPs. Also termed *lead span*.

Channel: A plastic container, in the form of a long tube, in which a number of DIPs are placed in single file and oriented for dispensing to an insertion machine; also called *sticks*.

Clinch: The bending of a component lead end after insertion through the PCB. This temporarily secures the component prior to soldering. In a full clinch, the lead is bent to contact the terminal area. In a modified clinch, the lead is partially bent to a predetermined intermediate angle.

Component: Any electrical device to be attached to the PCB.

DIP: Dual in-line package (Figure 9.2). A rectangular integrated circuit, packaged so as to terminate in two straight rows of pins or leads.

ECO: Engineering change order. A component or insulated jumper wire, installed manually, that is needed when the electrical circuit cannot be etched onto the board without crossing paths at some point. Often the leads are not inserted into the board but are manually soldered to the leads of components already assembled to the board. ECO wires are also referred to as *jumper wires*. (see *Retrofit*.)

Fault: Any error that causes the assembled PCB to fail testing procedures and that requires rework.

Hybrid: A PCB populated by both surface-mount and through-hole components; also referred to as *mixed-mounting* technology.

Insertion: Process whereby the component is grasped, prepared if necessary, placed on the board, and temporarily secured if necessary.

Kitting: Preparing a package of parts, usually with instructions for assembly, to facilitate manual assembly.

Magazine: A unit containing a group of dispensing channels, usually about 15, used for an automatic DIP insertion machine.

Module: A unit containing a group of dispensing spools, usually 20 or less, used with an automatic axial-lead component sequencer.

Nonstandard component: Any component that cannot be inserted by dedicated automatic machinery because of its physical characteristics, i.e., size, shape, lead span, etc., also called *odd-form* components.

Pallet: A tray on which components are arranged in a known position and orientation.

PCB: Printed-circuit-board. An insulating board onto which an electrical circuit has been printed in the form of conductive paths; contains drilled holes into which the leads of components are inserted; also known as a *printed wiring board* (PWB).

Preform: Forming the leads of a component to the correct dimensions prior to insertion. Axial-leaded components must usually have their leads bent at right angles for insertion, and DIPs sometimes require lead or pin straightening. Radial-leaded components may have their leads notched or a stand-off or spacer installed, which maintains the required clearance between the component and the board. Can-type ICs and transistors often need a type of lead forming called *form a*, which refers to the profile of the leads after forming.

Radial-lead component: Electrical components with leads at right angles to the body (Figure 9.2). Examples are disk capacitators, "kidney" or "jellybean" capacitators, cermet resistors, etc.

Reflow solder: Process by which SMDs become secured to the PCB.

Retrofit: A type of ECO that involves only the assembly of wires (jumper wires) to the PCB; can refer to an assembly station in the PCB assembly process where only wires are assembled.

Rework: Repair a fault. This usually means severing the leads of the component and removing it, removing the individual leads from the PCB holes, cleaning the holes, inserting a new component, and soldering its leads. The operations are performed manually and are time-consuming and expensive.

Sequencer: A machine that arranges components on a tape spool in the correct order for insertion.

SIP: Single in-line package. An integrated circuit, usually a resistor network or a connector, packaged so as to terminate in one straight row of pins or leads (Figure 9.2).

Sleeve: An insulating plastic tube slipped manually onto the lead of a component prior to insertion to guard against electrical short circuits (Figure 9.2).

SMD: Surface-mount device. A component (often leadless) that is secured to the surface of the board.

Spacer: This can be a small plastic ring (Figure 9.2) used to keep a minimum clearance between the component and the board. It is usually cemented to the board before the component is inserted. Some components use temporary spacers that are removed after the component is secured. Some spacers are provided with holes corresponding to each lead (Figure 9.2).

Spool: The package for holding taped axial-leaded components.

Standard component: Any component that can be inserted by an automatic insertion machine.

Stick: A plastic container in which a number of DIPs are aligned in single file and are oriented for dispensing to an automatic insertion machine.

Surface mount: See SMD.

Tin: Provide a layer of solder on the surface of leads prior to insertion.

Touch-up: Cleaning the underside or solder side of a PCB after wave-soldering to remove any excess solder that can cause short circuits.

Transistor: A small component whose body has a cylindrical envelope except for one flat face, with three leads at right angles to the body (Figure 9.2).

VCD: Variable center distance. The capability of an axial-lead component insertion head to vary the distance between leads when forming and inserting an axial-lead component (Figure 9.2). The term is also used to refer to an axial-lead component. The terms *adjustable span* and *variable span* can also be used.

Wave-solder: To solder automatically all the leads on an assembled PCB by conveying it, at a slight incline, over a wave of solder.

REFERENCES

1. John, J. and Boothroyd, G., Economics of Printed Circuit Board Assembly, Report 6, Economic Application of Assembly Robots Project, University of Massachusetts, Amherst, MA, April 1985.
2. Russell, G.A., Boothroyd, G., and Dewhurst, P., Printed Circuit Board Design for Assembly, Report 5, Product Design for Manufacture Program, Department of Industrial and Manufacturing Engineering, University of Rhode Island, Kingston, RI, May 1986.
3. Boothroyd, G. and Shinohara, T., Component Insertion Times for Electronics Assembly, *International Journal of Advanced Manufacturing Technology*, Vol. 1, no. 5, 1986, p. 3.

10 Feasibility Study for Assembly Automation

This chapter brings together the results of work in all the various aspects of assembly. After a careful analysis of the product design, the designer of an assembly machine must produce a proposal that combines many requirements. Some of these requirements, such as reliability and durability, are similar to those for any machine tool. However, certain requirements are applicable only to the assembly machine and are mainly a result of the variations in the quality of the component parts to be assembled. It can reasonably be assumed that an assembly machine can be designed that, if fed only with carefully inspected parts, will repeatedly perform the necessary assembly operations satisfactorily. Sometimes, unfortunately, the real problems of automatic assembly appear only when the machine is installed in the factory and the feeders are loaded with production parts containing the usual proportion of defectives. The possible effects of feeding a defective part into an assembly machine are:

1. The mechanical workhead may be seriously damaged, resulting in several hours or even days of downtime.
2. The defective parts may jam in the feeder or workhead and result in machine or workhead downtime while the fault is corrected.
3. The part may pass through the feeder and workhead and spoil the assembly, thus effectively causing downtime equal to one machine cycle besides producing an assembly that must be repaired.

Often, large samples of the parts to be assembled are available when the assembly machine is designed and, clearly, the designer should take into account, at the design stage, the quality levels of the parts and the possible difficulties that may result from them. Even the choice of basic transfer system can significantly affect the degree of difficulty caused by defective parts and, therefore, most of the important decisions will be made by the machine designer before detailed design is considered. Basically, the object of design should be to obtain minimum downtime on the machine resulting from a defective part being placed in the feeding device. This was illustrated in Chapter 6, which dealt with the economics of multistation indexing assembly machines. It was shown that any reduction in the time taken to correct a fault caused by a defective part will reduce assembly costs by reducing the total machine downtime. The first section of this chapter discusses the various design factors that can help to ensure minimum downtime due to defective parts, and the second section describes a feasibility study in detail.

10.1 MACHINE DESIGN FACTORS TO REDUCE MACHINE DOWNTIME DUE TO DEFECTIVE PARTS

The first objective in designing feeders and mechanisms for use in automatic assembly is to ensure that the presence of a defective part will not result in damage to the machine. This possibility does not generally exist when the part is moving under the action of its own weight (that is, sliding down a chute) or being transported on a vibrating conveyor. However, if the part is being moved or placed in a positive way, it is necessary to arrange that the desired motion be provided by an elastic system. In this case, if a defective part becomes jammed, motion can be taken up in the spring members. For example, if a plunger is to position a part in an assembly, it would be inadvisable to drive the plunger directly by a cam. It would be better to provide a spring to give the necessary force to drive the plunger and use the cam to withdraw the plunger. With this arrangement, a jammed part would not damage the mechanism.

The next objective in design should be to ensure that a jammed part can be removed quickly from the machine. This can be facilitated by several means, some of which are as follows:

1. All feeders, chutes, and mechanisms should be readily accessible. External covers and shields should be avoided wherever possible.
2. Enclosed feed tracks, feeders, and mechanisms should not be employed. Clearly, one of the least expensive forms of feed track is a tube down which the parts can slide freely to the workhead. However, a jam occurring in a closed tube is difficult to clear. Although more expensive to provide, open rails are preferable in such cases so that the fault can be detected and rectified quickly.
3. An immediate indication of the location of a fault is desirable. This may be achieved by arranging for a warning light to be switched on and a buzzer to be sounded when an operation fails. If the warning light is positioned at the affected workhead, the technician will be able to locate the fault quickly.

It is necessary for the machine designer to decide whether to arrange for the machine to be stopped in the event of fault or whether to allow the spoiled assembly to continue through the machine. In Chapter 6, we saw that, in the usual circumstances, it is preferable to keep the machine running. However, it would be clearly undesirable to attempt further operations on the spoiled assembly. For this purpose, the memory pin system can be employed, in which each work carrier is fitted with a pin which, in the event of a failure, is displaced by a lever fitted to the workhead. Each workhead is also provided with a feeler that senses the position of the pin before carrying out the operation. If the pin is displaced, the operation is not carried out. A microprocessor can accomplish this same effect with the appropriate software and electronic control.

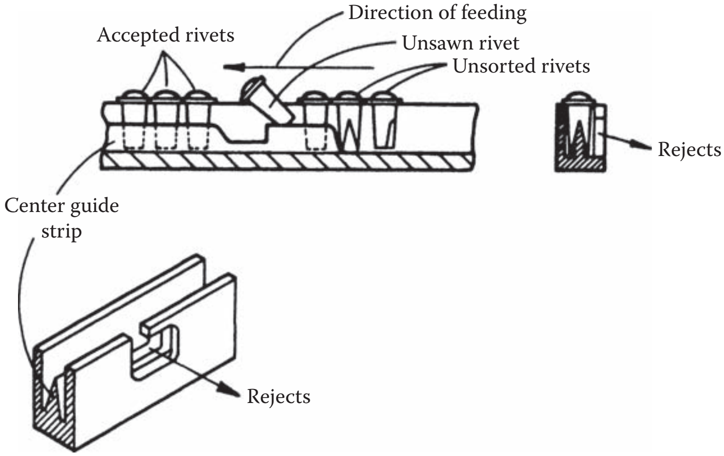


FIGURE 10.1 System for inspecting bifurcated rivets. (From Ward, K.A., Fastening Methods in Mechanized Assembly, Paper presented at the Conference on Mechanized Assembly, Salford University, England, July 1966. With permission.)

The difficulty with the memory pin system is that it is not possible for the workhead to detect immediately whether a particular fault will be repetitive. One possibility is to arrange that, initially, any type of fault will displace the memory pin but when two or three faults have occurred in succession, the machine is automatically stopped. Alternatively, it may be left to a technician to keep watch and stop the machine when a succession of faults occurs.

The preceding discussion dealt with methods of reducing machine downtime caused by defective parts. Ideally, of course, the defective parts would be detected and rejected in the feeding devices. Although it is generally not possible to perform complete inspection during the feeding of parts, it is sometimes possible to eliminate a considerable proportion of the defective parts. Figure 10.1 shows an example given by Ward [1] in which unsawn bifurcated rivets are detected and rejected in a bowl feeder. In this case, the device was incorporated to prevent unsawn rivets from being fed to the riveting head, where they could damage the mechanism during the operation. Sometimes, small pieces of swarf and other foreign bodies find their way into a bowl feeder, and a simple way of rejecting these is illustrated in Figure 10.2. Quite sophisticated inspection arrangements can be built into a bowl feeder, and it has been found economical in some circumstances to develop such a device to inspect the parts before they are placed in the assembly machine feeders. With this arrangement, the downtime occurs on the inspection device instead of on the assembly machine.

10.2 FEASIBILITY STUDY

The decision to build or purchase an automatic assembly system is generally based on the results of a feasibility study. The object of this study is to predict

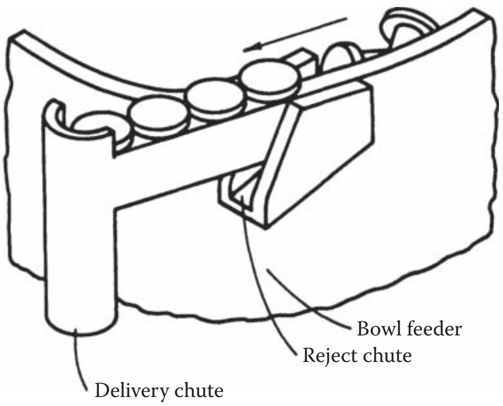


FIGURE 10.2 System for rejecting foreign matter in vibratory-bowl feeder. (From Ward, K.A., Fastening Methods in Mechanized Assembly, Paper presented at the Conference on Mechanized Assembly, Salford University, England, July 1966. With permission.)

the performance and economics of the proposed system. In automatic assembly, these predictions are likely to be subject to greater errors than in most other types of production equipment, mainly because the system is probably one of a kind and its performance depends heavily on the qualities of the parts to be assembled. Also, similar systems will not generally be available for study. Nevertheless, a feasibility study must be made, and all the knowledge and experience acquired in the past from automatic assembly projects must be applied to the problem in order to give predictions that are as accurate as possible.

Certain information is clearly required before a study can be made. For example, maximum and minimum production rates during the probable life of the machine must be known. The range of variations in these figures is important because a single assembly machine is quite inflexible. The personnel required on the machine must all be present when the machine is working or, if the machine is stopped because of a falloff in demand for the product, they must be employed elsewhere. Thus, automatic assembly machines are generally suitable only when the volume of production is known to be steady. Further, they can usually be applied profitably only when the volume is high. Apart from this high-volume requirement, the labor costs of the existing assembly process must also be high if automatic assembly is to be successful.

Clearly, much more information will be required and many other factors will combine to determine the final answer. Some of these are discussed in greater detail in the following text.

10.2.1 Precedence Diagrams

It is always useful when studying the assembly of a product to draw a diagram that shows clearly and simply the various ways in which the assembly operations may be carried out. In most assemblies, there are alternatives in the order in

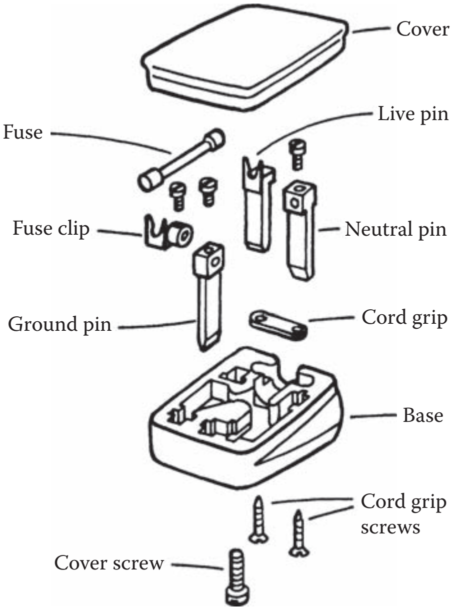
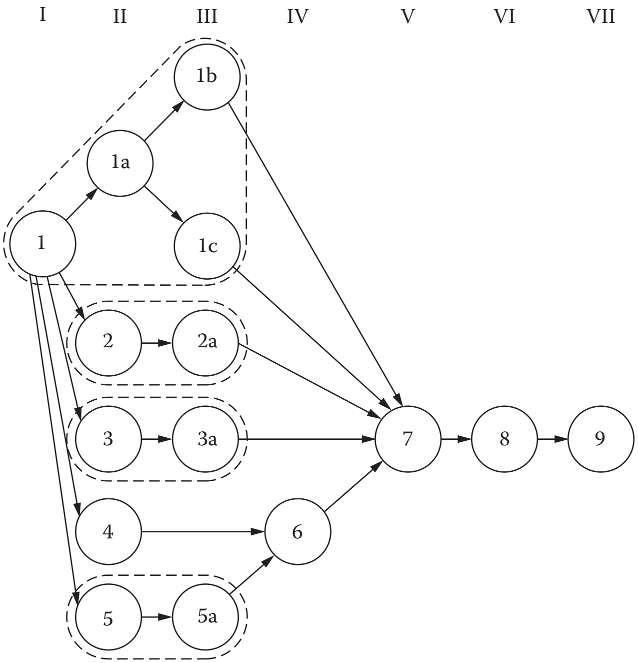


FIGURE 10.3 Three-pin power plug.

which some of the parts may be assembled. There are also likely to be some parts for which no flexibility in order is allowed. For example, in the three-pin power plug shown in Figure 10.3, the pins may be placed in position in any order, but the fuse can be inserted only after the fuse clip and live pin are in position. Further, the cover can be placed in position and secured only after all the remaining parts have been assembled into the base. The precedence diagram is designed to show all these possibilities, and its use has been described in detail by Prenting and Battaglin [2]. A precedence diagram for the assembly of the power plug, assuming that no subassemblies are involved, is shown in Figure 10.4, where it can be seen that each individual operation has been assigned a number and is represented by a circle with the number inscribed. The circles are connected by arrows showing the precedence relations.

In the precedence diagram, all the operations that can be carried out first are placed in column I. Usually, only one operation appears in this column: the placing of the base part on the work carrier. Operations that can be performed only when at least one of the operations in column I has been performed are placed in column II. Lines are then drawn from each operation in column II to the preceding operations in column I. In the example in Figure 10.4, none of the column II operations can be performed until the base of the power plug has been placed on the work carrier and, therefore, lines are drawn connecting operations 1a, 2, 3, 4, and 5 to operation 1. Third-stage operations are then placed in column III, with appropriate connecting lines, and so on, until the diagram is complete. Thus, following all the lines from a given operation to the left indicates all the



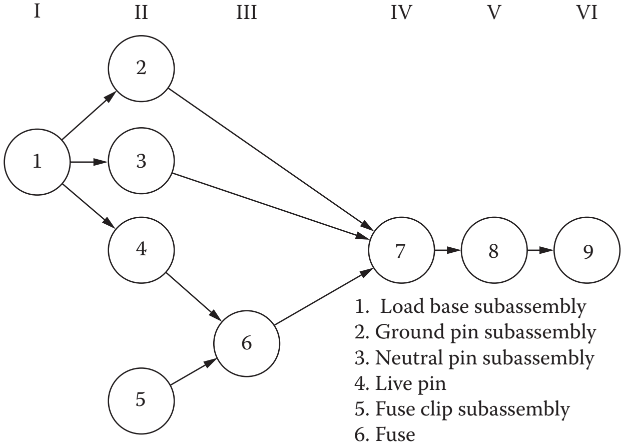
1. Load base onto work carrier
1a. Cord grip
1b. Cord grip screw
1c. Cord grip screw
2. Ground pin
2a. Ground pin screw
3. Neutral pin
3a. Neutral pin screw
4. Live pin
5. Fuse clip
5a. Fuse clip screw
6. Fuse
7. Cover
8. Cover screw
9. Remove complete assembly

FIGURE 10.4 Precedence diagram for complete assembly of power plug.

operations that must be completed before the operation under consideration can be performed.

In the assembly of the power plug, there are 15 operations, and it will probably be impracticable to carry out all these on a single machine. For example, it would be difficult to assemble the cord grip and the two cord grip screws while the plug base is held in a work carrier, because these parts enter the base from different directions. It is probably better, therefore, to treat these parts as a subassembly, and this is indicated in Figure 10.4 by the dashed line enclosing the necessary operations. In a similar way, the neutral and ground pins and the fuse clip, together with their respective screws, can also be treated as subassemblies. These groups of operations are all indicated by the dashed lines in Figure 10.4.

One of the objectives in designing an automatic assembly machine should be to include as few operations as possible on the line in order to keep machine downtime to a minimum. It is desirable, therefore, to break the product down



1. Load base subassembly
2. Ground pin subassembly
3. Neutral pin subassembly
4. Live pin
5. Fuse clip subassembly
6. Fuse
7. Cover
8. Cover screw
9. Remove complete assembly

FIGURE 10.5 Precedence diagram for assembly of power plug subassemblies.

into the smallest number of subassemblies and carry out individual studies of the subassemblies. If these subassemblies can be performed mechanically, separate machines may be used. These machines can then be arranged to feed the main assembly machine at the appropriate points.

Figure 10.5 shows the precedence diagram for the subassemblies of the power plug. It can be seen that no flexibility exists in the ordering of operations 1, 7, 8, and 9. Operations 2, 3, 4, 5, and 6, however, can be carried out in any order between operations 1 and 7 except that 6 cannot be performed until both 4 and 5 are completed. Considering the group of operations 4–6 first, there are two ways in which these can be performed: either 4, 5, 6 or 5, 4, 6. Operation 3 could be performed at any stage in this order, giving 4 × 2 = 8 possibilities. Thus, the precedence diagram shown in Figure 10.5 represents 40 possible orderings of the various assembly operations and will be useful when we consider the layout of the proposed assembly machine.

10.2.2 MANUAL ASSEMBLY OF PLUG

Before embarking on a detailed study for automatic assembly, it is necessary to analyze the product for manual assembly. This provides not only a benchmark for economic justification but also information on manual handling and assembly for any parts that do not lend themselves to automatic handling and assembly.

Table 10.1 presents the results of a manual assembly analysis carried out using the procedures described in Chapter 7. The total manual assembly time is 43 sec, with a corresponding cost of 36 cents for an assembly worker rate of $30/h. With an efficiency of 80% for the assembly plant, the manual assembly cost would be 45 cents.

TABLE 10.1
Analysis of Power Plug for Manual Assembly

		Handling Code	Handling Time (sec)	Insertion Code	Insertion Time (sec)	Total Time (sec)	Cost (cents)	Minimum Parts
1	Base sub	30	1.95	00	1.5	3.5	2.9	1
2	Fuse clip sub	35	2.73	00	1.5	4.2	3.5	1
3	Live pin	20	1.80	00	1.5	3.3	2.8	1
4	Fuse	00	1.13	31	5.0	6.1	5.1	1
5	Ground pin sub	20	1.80	00	1.5	3.3	2.8	1
6	Neutral pin sub	20	1.80	00	1.5	3.3	2.8	1
7	Cover	30	1.95	06	5.5	7.4	6.2	1
8	Reorientation	—	—	98	4.5	4.5	3.8	—
9	Cover screw	10	1.50	38	6.0	7.5	6.3	0
	Totals					43.2	36.2	7

DFA Index = 7 × 2.88/43.1 = 47%.

The DFA Index for the plug is very high at 47%, mainly because all the items except the cover screw must, of necessity, be separate from one another.

10.2.3 QUALITY LEVELS OF PARTS

If assembly of a completely new product is to be contemplated, the estimation of the quality levels of the parts may be extremely difficult, if not impossible. However, a large proportion of assembly machine feasibility studies are concerned with existing products and, in these cases, experiments can be performed to determine the quality levels of the various parts. It should be remembered in such a study that defective parts do not generally create great difficulties when assembly is performed by hand. Often, the assembly worker can quickly detect and reject a defective part and, in many cases, when the "defective part" is simply a nonpart, such as a piece of swarf or bar end, the assembly worker does not even attempt to grasp it but simply leaves it in the parts container to be discarded later. This means that a study of quality level must be conducted at the existing assembly stations, where the numbers of discarded parts and foreign bodies can be recorded. A further danger is that engineers responsible for assembly processes often assume that 100% visual inspection results in 100% acceptable parts. The assumption that an inspection worker inspecting every part that is to be assembled will detect every defective part is clearly not valid.

The best procedure for estimating quality levels is for the investigator to observe the assembly work and note every defective part or foreign body that is discarded. Obviously, it is inadvisable to assume that the quality levels recorded cannot be improved upon, but it is necessary to estimate the cost of these improvements and to allow for this extra cost in the feasibility study.

TABLE 10.2
Quality Levels of Power Plug Parts

Parts	Fault	Number of Faults in Assembling 10,000 Plugs	Percentage Faults
Base subassembly	Chipped	10	0.10
	Ground pin will not assemble	170	1.70
	Live pin will not assemble	20	0.20
	Neutral pin will not assemble	30	0.30
Earth pin subassembly	No screw	41	0.41
Neutral pin	No screw	59	0.59
Live pin subassembly	Fuse will not assemble	123	1.23
	Fuse assembles unsatisfactorily	21	0.21
Fuse clip subassembly	Fuse will not assemble	115	1.15
	Fuse assembles unsatisfactorily	17	0.17
Fuse	Damaged	18	0.18
Cover	Chipped	10	0.10
	Cover screw hole blocked	200	2.00
Cover screw	No thread or slot	20	0.20

Having noted the number of defective parts in a given batch, the investigator can then divide these into two categories: (1) those parts that cannot be assembled, for example, screws with no thread or slot; and (2) those parts that can be assembled but are normally rejected by the operator, for example, discolored or chipped parts.

The number of parts falling in the first category allows estimates to be made of the assembly machine downtime, and the number of those falling in the second category allows estimates to be made of the number of unacceptable or defective assemblies produced by the machine.

Figures for the power plug shown in Figure 10.3 are presented in Table 10.2. It is important to remember that no assessment can be made of the most suitable type of assembly machine or of the number of operations that can economically be performed mechanically until the individual quality levels of the various parts have been investigated.

10.2.4 PARTS FEEDING AND ASSEMBLY

An estimate must now be made of the degree of difficulty with which the individual parts can be automatically fed and assembled. It should be noted here that, for each operation, four possibilities exist:

1. Automatic feeding and assembly
2. Manual feeding and automatic assembly

3. Automatic feeding and manual assembly
4. Manual feeding and assembly

For this feasibility study on power plug assembly, it is assumed that an annual production volume of 1.5 million plugs is planned with two-shift working. For a product life of 36 months, this represents a total life volume of 4.5 million assemblies, assuming an efficiency of 80%. An assembly rate of 7.8/min would be required while the assembly system is in operation, giving an average production time or cycle time of 7.7 sec. This figure includes any downtime due to faulty parts.

With regard to the feeding of parts, all but the simplest shapes will probably require vibratory-bowl feeders, and simple experiments can normally be performed to test various ideas for orienting and feeding. Estimates can then be made of the various feed rates possible. For a given bowl feeder, the maximum feed rate obtainable is proportional to the reciprocal of the length of the part, assuming that all parts arrive at the bowl outlet end to end. Thus, with large parts that have many possible orientations, only one of which will be required, the feed rate of oriented parts can be very low.

For example, the base subassembly of the power plug shown in Figure 10.3 is 49-mm long and can be fed along a bowl feeder track in any of eight possible orientations. Thus, suitable devices will have to be fitted to the track of the bowl to reject seven of the eight orientations. The maximum feed rate of oriented parts will be given by Equation 3.49. Thus,

$$F_m = \frac{vE}{\ell} \tag{10.1}$$

where v is the mean conveying velocity (25 mm/sec), ℓ the length of the part, and E the modified efficiency of the orienting system (see Equation 3.50). The automatic handling code for the base subassembly is obtained as follows:

1. The overall dimensions of this nonrotational subassembly are $A = 49$ mm, $B = 47$ mm, $C = 12$ mm. Thus, $A/B < 3$, and $A/C > 4$. From Figure 8.3, therefore, the first digit of the geometrical code is 6.
2. The part has no symmetry about any axis, and the principal features that can be used for orienting purposes are the two screws that appear as an asymmetric projection or step when the subassembly is viewed in the Y direction. Thus, from Figure 8.5, the second and third digits are 4 and 1, respectively.
3. In a vibratory-bowl feeder, parts circulate and tumble from the tracks into the bottom of the bowl repeatedly. This part is manufactured from hard plastic, and care must be taken not to damage its surfaces. For a delicate part such as this, Figure 8.8 gives fourth and fifth digits of 2 and 0, respectively.

4. The five-digit code is therefore 64120, giving, from Figure 8.5, an orienting efficiency of 0.15 and a relative feeder cost of 1. With an additional feeder cost of 1 from Figure 8.8, we get a total relative feeder cost of 2.

Using Equation 10.1, the estimated maximum feed rate from one feeder would be

$$F_m = 49 \times \frac{0.15}{25} = 4.6\ \text{parts / min}$$

To meet the required feed rate of 7.8 parts/min, two feeders would be required or, alternatively, a sum equivalent to the cost of 1.7 feeders could be spent on the development of a special feeder to meet the required delivery rate. In the present case, if the basic feeder cost is \$7K, the total sum would be \$23.8K.

Bearing these points in mind, the designer decides whether automatic feeding of the particular part is feasible. In the example of the power plug, it is possible that both the base subassembly and the cover could not be fed at the required rate from one feeder and that the fuse clip assembly, because of its complicated shape, would have to be handled manually. The remaining parts and subassemblies could probably all be fed and assembled automatically with bowl feeders and placing mechanisms, with the exception being the main holding screw, which would have to be fed and screwed from below with a proprietary automatic screwdriver.

10.2.5 SPECIAL-PURPOSE MACHINE LAYOUT AND PERFORMANCE

10.2.5.1 Indexing Machine

If it is assumed that the base, top, and fuse clip are to be assembled manually on an in-line indexing machine, at least two assembly workers will be required. The first, positioned at the beginning of the line, could place the base subassembly on the work carrier and place the fuse clip assembly in the base (operations 1 and 5 of Figure 10.5). The second assembly worker could assemble the cover and remove the complete plug assembly from the end of the line (operations 7 and 9 of Figure 10.5).

It is generally necessary to include some inspection stations on an assembly machine. In the present example, it is clear that after the plug cover has been assembled, there will be no simple means of inspecting for the presence of the fuse clip, the fuse, and the three small screws in the neutral and ground pins, and the fuse clip. Thus, it will be necessary to include an inspection head on the machine immediately before operation 7 (the assembly of the cover), which will check for the presence of all these parts.

In the present example, it is also necessary to decide whether the inspection head should be designed to stop the machine in the event of a fault or to prevent

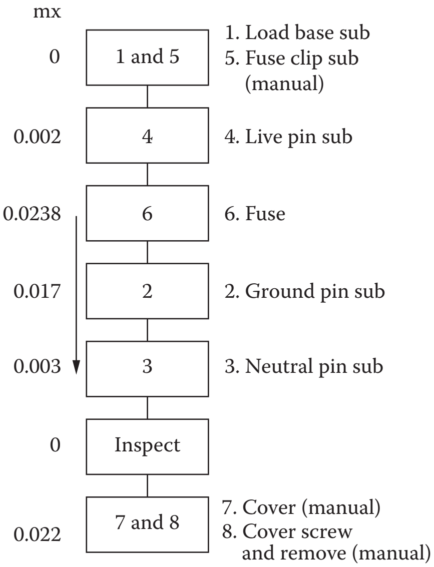


FIGURE 10.6 Station layout of in-line indexing machine for assembling power plugs.

further operations being performed on the assembly. In the following studies, it will be assumed that a memory system has been incorporated, with the inspection head designed to activate the memory system rather than to stop the machine.

The general layout of a suitable in-line indexing machine is shown in Figure 10.6. Note that operations 4 and 6 have been arranged immediately after the first (manual) station to minimize the possibility of the fuse clip becoming displaced during the machine index. When the fuse is in position, the fuse clip is then positively retained. These desirable features provide further restrictions in the order of assembly, and the precedence diagram is modified as shown in Figure 10.7.

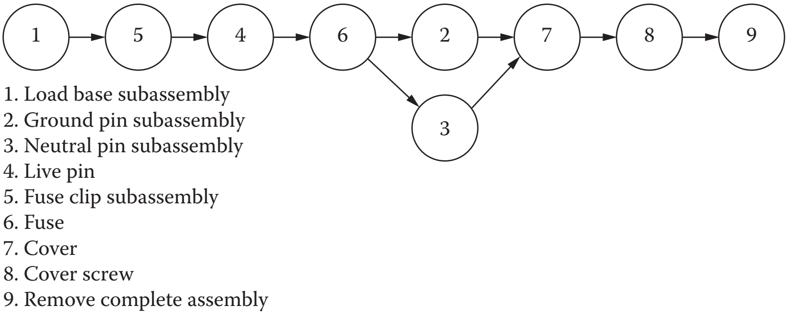


FIGURE 10.7 Final precedence diagram for assembly of power plug.

The downtime on an indexing machine is given by the sum of the downtimes on the individual heads due to the feeding of defective parts plus the effective downtime due to the production of unacceptable assemblies.

If, for each machine station, x is the effective proportion of defective to acceptable parts, then mx is the average proportion of defectives that will cause a machine stoppage, and $(1 - m)x$ is the effective average proportion of defectives that will spoil the assembly but not stop the machine. The downtime due to machine stoppages and the final production rate are found as follows:

In the production of N assemblies, the number of machine stoppages is $N\Sigma mx$, where Σmx is the sum of the individual values of mx for the automatic workheads. If T is the average time to correct a fault and restart the machine, the downtime due to machine stoppages is $NT\Sigma mx$; if t is the machine cycle time, the proportion of downtime D will be given by

$$D = \frac{\sum mx}{t\ /\ T + \sum mx} \tag{10.2}$$

The figures in Table 10.2 are rearranged in Table 10.3 to give the effective quality levels for the various operations. From these figures, it can be seen that the value of Σmx is 0.0678 and, assuming that t = 7.7 sec (the time taken to place

TABLE 10.3
Effective Quality Levels in Power Plug Assembly

	Operation	Automatic Station on Indexing Machine	Effective Quality Level (*x*)	Ratio of Defectives Causing Machine Stoppages (*m*)	*mx*	*(1m)x*
1	Assemble base subassembly onto work carrier	—	0.001	0	0	0.001
2	Assemble ground pin subassembly into base	4	0.017	1.0	0.017	0
3	Assemble neutral pin subassembly into base	5	0.003	1.0	0.003	0
4	Assemble live pin into base	2	0.002	1.0	0.002	0
5	Assemble fuse clip subassembly into base	—	0	0	0	0
6	Assemble fuse into live pin and fuse clip	3	0.294	0.813	0.0238	0.0056
7	Assemble cover	7	0.001	0	0	0.001
8	Assemble cover screw	7	0.022	1.0	0.022	0
9	Remove complete assembly	—	0	—	—	—
10	Inspection	—	0.01	0	0	0.01
	Totals				0.0678	0.0176

the base subassembly on the work fixture and assemble the fuse clip) and that $T = 40$ sec, then,

$$D = \frac{0.0678}{7.7/40 + 0.0678} = 0.26 \; (26\%)$$

Some of the assemblies produced will contain defective parts that did not stop the machine and, assuming that no assembly contains more than one such defective part, the production rate of acceptable assemblies P_a will be given by

$$P_a = \frac{[1 - \sum(1-m)x](1-D)}{t} \tag{10.3}$$

From Table 10.3, $\Sigma(1-m)x = 0.0176$ and, therefore, from Equation 10.3,

$$P_a = \frac{(0.9824)0.74}{7.7} = 0.094 \;\; \text{assemblies/sec (5.7 assemblies/min)}$$

This corresponds to an overall assembly time of 10.5 sec, and it would be necessary to supplement the machine with some manual assembly in order to meet the required production rate of 7.8 assemblies/min.

10.2.5.2 Free-Transfer Machine

The layout of a free-transfer machine suitable for assembling the power plug would be the same as that for an indexing machine (Figure 10.6). It will be assumed in the following description that each workstation is capable of accommodating six work carriers, one of which is situated below the workhead, with the remaining five constituting the buffer storage.

Using a basic cycle time of 7.7 sec and a downtime per fault of 40 sec as before, and the proportions of parts at each station causing a fault (mx) from Table 10.3, a computer simulation was carried out. It was assumed that one technician tended the machine in order to correct faults. The simulation gave an estimated downtime of 14.1% and showed that the technician would be occupied 30% of the time.

The average cycle time for these conditions was 8.96 sec, giving an average assembly rate of 6.7 assemblies/min. Although this figure is higher than that for the indexing machine because of the reduced downtime, the output would again have to be supplemented by manual assembly.

A complete analysis of the automatic assembly of each of the items in the power plug is presented in Table 10.4, where it can be seen that, of the parts that are to be fed automatically, the ground pin sub and the neutral pin sub give a maximum feed rate that is less than the 7.8 parts/min required. This means that

TABLE 10.4
Analysis of Power Plug for High-Speed Automatic Assembly

		Handling Code	Orienting Efficiency	Relative Feeder Cost	Maximum Feed Rate per min	Insertion Code	Relative Workhead Cost
1	Base sub	64120	0.15	(2)	4.6	(Manual assembly selected)	
2	Fuse clip sub	84044	0.15	(5)	11.3	(Manual assembly selected)	
3	Live Pin	71200	0.25	2	10.1	00	1.0
4	Fuse	20000	0.90	1	54.0	31	1.9
5	Ground pin sub	71100	0.15	1.33	5.8	00	1.0
6	Neutral pin sub	71100	0.15	1.1	7.0	00	1.0
7	Inspection	—	—	—	—	—	1.0
8	Cover	64620	0.10	(3)	3.1	(Manual assembly selected)	
9	Cover screw	21000	0.90	1	75.0	48	1.3
	Totals			6.43			7.2

Notes: Codes and data obtained from Figure 8.3 to Figure 8.5.
Relative feeder costs in parentheses not added into total because manual assembly selected.

for the ground pin sub, an additional 33% has to be added to the feeder cost in order to provide the required rate and, similarly, for the neutral pin sub 10% can be added.

Summing the appropriate relative feeder costs gives 6.43 and, multiplying this figure by the basic feeder cost of $7K, the total cost of feeders would be $45K. Similarly, the total relative workhead cost is 7.2 and, for a basic workhead cost of $10K, this gives a total of $72K.

For the indexing machine, assuming a cost per station of $10K for the transfer device and controls and an additional $1K per station for the work carrier, we get $77K for seven stations, giving a total equipment cost of $194K.

In this comparison, we employ the simple payback method for estimating the cost of using equipment and, therefore, using a value of Q_e (the capital equivalent of one assembly worker) of $90K, two-shift working, and an assembly worker rate of 0.83 cent/sec ($30/hr), the rate for the equipment is 0.9 cent/sec.

If the rate for the technician is 1.1 cents/sec, the total for two assembly workers and one technician is 2.8 cents/sec, giving a total rate for the machine and personnel of 3.7 cents/sec. It was estimated earlier that the average assembly time for the indexing machine would be 10.5 sec and, therefore, the cost per assembly would be 38.9 cents. With an efficiency of 80%, this cost increases to 48.6 cents, a figure that is comparable with the cost of 45 cents for manual assembly.

For the free-transfer machine, assuming that the cost for each station with five buffers and all controls is $30K and that there are three work carriers per station (costing $1K each), the total for the seven-station machine is $348K, including feeders and workheads. This corresponds to a rate of 1.6 cents/sec, giving a total rate for the machine and personnel of 4.4 cents/sec. Finally, for an assembly rate of 6.7 assemblies/min (8.96-sec cycle) and an efficiency of 80%, the total assembly cost is 49.3 cents.

This figure is slightly higher than that for an indexing machine, but this is to be expected because the benefits of the nonsynchronous arrangement become apparent only when machines have relatively large numbers of stations. Also, with both machines, the two assembly workers and the technician are underutilized, leading to a higher cost than that for manual assembly.

One of the principal problems was the manual assembly of the base subassembly, the cover, and the fuse clip subassembly and, ideally, the calculations should be repeated for configurations other than the one considered here. For example, if one assembly worker could be eliminated by feeding and orienting all the parts, the total feeder cost would be \$157K, increasing the total equipment costs by \$112K. However, an extra station would be required at the beginning of the machine, costing an extra \$11K and giving a new total equipment cost for an indexing machine of \$317K, an increase of almost 40%. Assuming that the machine could now produce assemblies at the required rate of 7.8/mm (i.e., every 7.7 sec), the new assembly cost would be 32.6 cents, including the 80% efficiency factor. However, for comparison purposes, we shall continue with the original configuration, assuming that it is desirable to minimize the investment in equipment.

10.2.6 Robot Assembly of the Power Plug

The use of robots in assembly allows greater flexibility in part-presentation methods. We assume that the base subassembly, cover, and fuse clip subassembly are presented in magazines that have been loaded manually. For each magazine, we make an allowance of \$1.5K, and we use the manual handling time for the items, plus 1 sec for insertion into the magazine.

Table 10.5 presents the results of an analysis for a single-station system with one robot arm. A cost of \$12K is assumed for the basic work fixture, with an additional \$12.5K for a special automatic screwdriver that inserts the cover screw from below. Also, \$10K is allowed for the inspection head, which would be attached to the work fixture. A standard SCARA-type robot (estimated cost \$80K) can perform all the remaining assembly operations. The total feeder and magazine cost is estimated to be \$39.5K, and the assembly worker time for loading magazines is 9.7 sec per assembly. Because these operations are carried out off-line, this time can be multiplied by the assembly worker rate of 0.83 cent/sec, giving a cost of 8.05 cents for magazine loading. Total equipment costs of \$154K would give a rate of 0.71 cent/sec. One of the advantages of single-station robot systems is that the downtime due to defective parts forms a relatively small proportion of the total cycle. This means that one technician can tend to several systems. In the present case, the total operation time is 22 sec. The average downtime occurring on each cycle is $T\Sigma mx$ sec or, with $\Sigma mx = 0.0678$ and $T = 40$ sec, the downtime per cycle is 2.7 sec, giving a total cycle time of 24.7 sec. Therefore, three systems would be needed to meet the required production volume, which

TABLE 10.5
Analysis of Power Plug for Single-Station One-Arm Robot Assembly

		Robot Insertion Code	Robot Cost (in thousands of dollars)	Tool Cost (in thousands of dollars)	Fixture Cost (in thousands of dollars)	Part-Presenter Cost (in thousands of dollars)	Operation Time (sec)	Time for Manual Operations (sec)
1	Base sub	00	80	—	12.0	1.5	3.0	3.0
2	Fuse clip sub	00	80	—	—	1.5	3.0	3.7
3	Live Pin	00	80	—	—	7.0	3.0	—
4	Fuse	30	80	—	—	7.0	3.0	—
5	Ground pin sub	00	80	—	—	7.0	3.0	—
6	Neutral pin sub	00	80	—	—	7.0	3.0	—
7	Inspection	—	—	10	—	—	—	—
8	Cover	02	80	—	—	1.5	3.0	3.0
9	Cover screw	—	—	12.5	—	7.0	1.0	—
	Totals			22.5	12.0	39.5	22.0	9.7

Note: Codes and data obtained from Figure 8.21.

corresponds to one assembly every 7.7 sec while the systems are working. It would seem reasonable to assign one technician to tend all three systems at an additional rate of 0.37 cent/sec per system.

Thus, the total rate for the equipment and technician is 1.08 cents/sec which, with a cycle time of 24.7 sec, represents a cost of 26.7 cents. Finally, adding the cost of magazine loading (8.05 cents) and allowing for 80% efficiency gives an assembly cost of 43.4 cents for a single-station system with one robot arm.

Repeating the calculations for Table 10.6, a system with two robot arms gives a total cycle time of 16.5 sec (including downtime), a total equipment cost of $224K for one machine, and an assembly cost of 41.8 cents. In this calculation, two robot arms were assumed to cost $150K, and the technician was assigned to supervise two systems.

The final system to be considered is the multistation transfer machine with robots. The first step in considering this type of system is to assign tasks to the robots that can be accomplished within the cycle time that would give the production volume required.

In the present example, the required average production time is 7.8 assemblies/min corresponding to a cycle time of 7.7 sec.

Table 10.7 shows the results of an analysis for a multistation machine in which the various operations have been assigned to the workstations. It can be seen that a five-station machine is required. The first three stations have robots carrying out two assembly operations each; the fourth is an inspection station; and at the fifth, a robot places the cover, and a special screwing device mounted below the station inserts the cover screw.

The cost of each robot is $80K, each station with controls and work carriers costs $33K, the cost of magazines and feeders is $39.5K, the automatic screwdriver costs $12.5K, and the inspection head costs $10K. Summing these figures gives a total equipment cost of $547K. The system cycle time is 6 sec plus downtime, which is found from computer simulation to be 23.4%, with 35% of the technician's time spent in correcting faults. This downtime percentage corresponds to an average downtime/cycle of 1.8 sec and, therefore, the average cycle time is 7.8 sec. This figure closely matches that required and corresponds to a production rate of 7.7 assemblies/min.

With a rate for equipment of 2.52 cents/sec, together with the technician rate of 1.1 cents/sec, we get an assembly cost of 28.2 cents. Adding 8.05 cents for magazine loading and allowing for 80% efficiency gives a total assembly cost of 45.4 cents.

For the example of the power plug and the production conditions selected, all the alternative schemes give assembly costs close to those for manual assembly. The results are summarized in Table 10.8, where it can be seen that the single-station system with two robot arms might yield the best results. However, the capital investment is more than twice that for a special-purpose indexing machine. Also, as was shown, analyses of other special-purpose machine configurations should be carried out. In fact, it was seen that the use of two assembly workers on the system would not be the most economical arrangement.

TABLE 10.6
Analysis of Power Plug for Single-Station Two-Arm Robot Assembly

		Robot Cost (in thousands of dollars)	Tool Cost (in thousands of dollars)	Fixture Cost (in thousands of dollars)	Part-Presenter Cost (in thousands of dollars)	Operation Time (sec)	Manual Operation Time (sec)
1	Base sub	150	—	12.0	1.5	1.7	3.0
2	Fuse clip sub	150	—	—	1.5	1.7	3.7
3	Live pin	150	—	—	7.0	1.7	—
4	Fuse	150	—	—	7.0	1.7	—
5	Ground pin sub	150	—	—	7.0	1.7	—
6	Neutral pin sub	150	—	—	7.0	1.7	—
7	Inspection	—	10	—	—	—	—
8	Cover	150	—	—	1.5	2.6	3.0
9	Cover screw	—	12.5	—	7.0	1.0	—
	Totals		22.5	12.0	39.5	13.8	9.7

Note: Data obtained from Figure 8.22.

TABLE 10.7
Analysis of Power Plug for Multistation Robot Assembly

		Robot Cost (in thousands of dollars)	Tool Cost (in thousands of dollars)	Part-Presenter Cost (in thousands of dollars)	Operation Time (sec)	Workstation Number	Manual Operation Time (sec)
1.	Base sub	80	—	1.5	3	1	3.0
2.	Fuse clip sub	80	—	1.5	3	1	3.7
3.	Live pin	80	—	7.0	3	2	—
4.	Fuse	80	—	7.0	3	2	—
5.	Ground pin sub	80	—	7.0	3	3	—
6.	Neutral pin sub	80	—	7.0	3	3	—
7.	Inspection	—	10	—	1	4	—
8.	Cover	80	—	1.5	3.1	5	3.0
9.	Cover screw	—	12.5	7.0	1	5	—
	Totals		22.5	39.5			9.7

Note: Data obtained from Figure 8.23.

TABLE 10.8
Comparison of Results of Feasibility Study

			Multistation Special-Purpose		Robot Systems		
		Manual Assembly	**Indexing**	**Free-Transfer**	**1-Arm**	**2-Arm**	**Multistation**
Number of systems		6	1	1	3	2	1
Number of stations:	Manual	1	2	2	0	0	0
	Auto	—	6	6	0	0	1
	Robot	—	—	—	1	1	4
Total	Assembly	6	2	2	0	0	0
system workers	Tech	—	1	1	1	1	1
Total equipment costs[a]		—	194	348	462	448	547
Assembly rate/min		8.4	5.7	6.7	7.3	9.5	7.7
Assembly costs, cents		45.0	48.6	49.3	43.4	41.8	45.4

Note: Required rate of assembly while system in operation is 7.8 assembly/min; required cycle time is 7.7 sec.

[a] In thousands of dollars.

REFERENCES

1. Ward, K.A., Fastening Methods in Mechanized Assembly, Paper presented at the Conference on Mechanized Assembly, Salford University, England, July 1966.
2. Prenting, T.O. and Battaglin, R.M., The Precedence Diagram: A Tool for Analysis in Assembly Line Balancing, *Journal of Industrial Engineering*, Vol. 15, July–August 1964, p. 208.

Problems

1. A vibratory-bowl feeder is fitted with springs that are inclined at an angle of 60° to the horizontal. The upper portion of the bowl track is horizontal, and the frequency of operation is 60 Hz. The amplitude of vibration is adjusted such that the normal track acceleration has a maximum of 1.0*g* for the upper part of the track.
   a. If the coefficient of friction between the parts and the track is 0.5, will forward conveying be achieved by forward sliding only or by a combination of forward and backward sliding?
   b. What will be the maximum parallel track velocity ν_p (mm/sec)?
   c. If the conveying efficiency η is 70%, what will be the mean conveying velocity ν_m of the parts? Note that $\eta = (\nu_m/\nu_p) \times 100$.

2. A standard vibratory-bowl feeder has three leaf springs inclined at 80° to the horizontal. These springs are equally spaced around a circle of 225-mm radius and support a bowl that is 600 mm in diameter.
   a. Determine the effective vibration angle for the horizontal upper part of the bowl track.
   b. If the peak-to-peak amplitude of vibration in the line of vibration at the bowl wall is 2.5 mm and the frequency is 60 Hz, determine whether forward conveying will occur and whether this will be by both forward and backward sliding or by forward sliding only. (Assume that the coefficient of friction between the part and the track is 0.5.)
   c. If the feeding motion is 100% efficient, what would be the mean forward conveying velocity of the parts?

3 a. If a vibratory-bowl feeder is driven at a frequency of 60 Hz, with vibration angle of 20°, what peak-to-peak horizontal amplitude of vibration (mm) will give a mean conveying velocity of 50 mm/sec on a horizontal track?
   b. For the same conditions as those of part a, what would be the minimum vertical clearance between a part and a wiper blade so that the wiper blade will never reject the parts?
   c. If the leaf springs on the feeder are mounted at a radial position r_2 of 100 mm and the track radius r_1 is 200 mm, what spring angle (measured from the horizontal) will give the vibration angle of 20°?

4. A special decal on the side of a vibratory-bowl feeder indicates that the horizontal peak-to-peak amplitude of vibration is 0.25 mm. The

angle of the supporting springs is such that the vibration at the bowl wall is inclined at an angle of 20° to the horizontal. The coefficient of friction between the parts and the track is 0.2, the frequency of vibration is 60 Hz, and the track is inclined at 5° to the horizontal. Determine:

a. The actual value of A_n/g_n for the inclined track
b. The value of A_n/g_n for forward sliding to occur during the vibration cycle
c. The value of A_n/g_n for backward sliding to occur
d. Whether forward conveying will occur
e. Whether hopping will occur

5. A vibratory-bowl feeder has a spring angle of 70° and is operated at a frequency of 60 Hz. The radius to the springs is 150 mm and to the upper, horizontal part of the track is 200 mm. The amplitude of vibration is set so that the parts traveling around the upper track are on the verge of hopping.
   a. What is the horizontal (parallel) amplitude (a_p) of vibration at the bowl wall? Give the answer in μm.
   b. What is the minimum coefficient of friction between parts and track for forward conveying to occur?
   c. If the coefficient of friction is 0.3, what is the minimum value of the normal amplitude a_n (μm) for forward conveying to occur?

6. Derive an expression for the dimensionless maximum parallel distance jumped by a part, J / A_p^0, during each cycle of vibratory feeding (J = parallel distance jumped relative to the track amplitude). Assume that, for maximum distance jumped, $\omega t_2 = \omega t_1 + 2\pi$, where ω is the frequency in rad/sec, t_1 the time the part leaves the track, and t_2 the time the part lands on the track. Also, assume that the coefficient of friction between the part and the track is such that the part never slides. If the efficiency of conveying is defined by $\eta = v_m(100)/ v_{p\max}$, where v_m is the mean conveying velocity and $v_{p\max}$ the maximum parallel track velocity, calculate the maximum efficiency possible under the conditions stated above, with a track angle of zero.

7. A vibratory-bowl feeder operates at a frequency of 60 Hz. The track angle is 5°, the vibration angle 40°, and the horizontal component of the amplitude of vibration of the track 10 mm. If the coefficient of friction between the parts and the track is 0.2, will the parts be conveyed up the track?

8. The peak-to-peak parallel amplitude of vibration at the wall of a vibratory-bowl feeder is 0.889 mm. The vibration angle is 10°, and the frequency of vibration is 60 Hz. Using the figures in the text determine:

- a. The mean conveying velocity
- b. The effective distance the part hops
- c. The height of the part hop
- d. The new conveying velocity if the frequency is reduced to 30 Hz and the amplitude increased threefold

9. a. If a vibratory-bowl feeder is driven at a frequency of 60 Hz and the vibration angle is 20°, what peak-to-peak horizontal amplitude of vibration (mm) will give a mean conveying velocity of 50 mm/sec on a horizontal track?
   b. For the same conditions as those of part (a), what would the minimum vertical clearance be between a part and a wiper blade so that the wiper blade will never reject the parts?
   c. If the leaf springs on the feeder are mounted at a radial position r_2 of 100 mm, and the track radius r_1 is 200 mm, what spring angle (measured from the horizontal) will give a vibration angle at the track of 20°?

(Use Figure 3.9 and Figure 3.11 in the text for parts [a] and [b].)

10. A vibratory-bowl feeder drive is adjusted so that hopping is just about to occur on the upper portion of the track that is inclined at 4°. The vibration angle for the upper track is 15° and the frequency of vibration is 30 Hz.
    a. What is the *horizontal* peak-to-peak amplitude of vibration in mm?
    b. What coefficient of friction between parts and track would be needed for the parts to be conveyed up the track?

11. In an 18-in.-diameter vibratory-bowl feeder, the track angle is 4° and the spring angle is 70°. The springs are mounted at a radius of 6 in.
    a. What is the effective vibration angle at the bowl track?
    b. What is the minimum coefficient of friction between parts and track for forward conveying to be achieved on the inclined track?
    c. If the frequency of vibration is 60 Hz, what minimum parallel amplitude of vibration will cause the parts to hop during the conveying motion?

12. A horizontal linear vibratory feeder has a spring angle of 80°. and operates at 60 Hz. With the amplitude set so that the parts are on the verge of hopping, the conveying speed is 10 mm/sec. If the feeder were to be operated at 30 Hz and the amplitude increased until the parts are again on the verge of hopping, what will be the new conveying speed? By what ratio will the amplitude have been increased?

Hint: remember that $v\omega/g$ = function (A/g, θ, ψ, μ).

13. A problem is encountered with a horizontal linear vibratory conveyer having a spring angle of 80°, operating at 60 Hz and set with a horizontal amplitude of 0.2 mm. The conveying speed required is 100 mm/sec, but this cannot be achieved.
    It is suggested that the operating frequency might be reduced to 30 Hz and the amplitude increased.
    a. What is the original conveying speed to the nearest 10 mm/sec?
    b. What should the new amplitude be?

Use Figure 3.9 in the text.

14. Parts in the form of right circular cones having a height H and a base radius R are to be fed and oriented using a vibratory-bowl feeder. The bowl track is designed so that a part will be fed to the orienting devices either standing on its base or lying on its side with the base leading or following. Two active orienting devices are to be used. The first is a step of height h_s, which will cause a part standing on its base to overturn onto its side but will not affect the remaining orientations. The second device consists of a portion of track with a V cross section so that all parts lying on their sides will fall into the V with their bases uppermost.

Determine the theoretical limits for the dimensionless height of the step (h_s/H) for the situation described, assuming that a very low conveying velocity is to be employed. Assume that the parts do not bounce or slide as they are fed over the step and that no energy is lost as the parts impact with the track, and that $H = 4R$.

15. A rivet feeder (external gate hopper) has a gate (at the lowest point in the feeder body) through which the rivets pass; the gate is 1.4d in width, where d is the diameter of the shank of the rivet. The rivets are tumbled within a rotating inner sleeve having slots to accept the rivet shanks that are just wide enough to accept one rivet. The gap between the inner sleeve and the body of the feeder is equal to 0.6d, and the distance between slots is 4.0d.
    a. Derive an expression, in terms of d, for the critical peripheral velocity of the inner sleeve to prevent jamming.
    b. Estimate the maximum feed rate in rivets/sec if the efficiency with which rivets fall into the slots is 30% and the diameter of the rivet shanks d is 5 mm.

16. A rivet feeder (external gate hopper) has a gate, through which the shanks of the rivets pass; the gate is 1.2d in width, where d is the diameter of the shank of the rivet. The rivets are tumbled within a rotating inner sleeve having slots to accept the rivet shanks that are

just wide enough to accept one rivet. The gap between the inner sleeve and the body of the feeder is equal to 0.5*d*, and the distance between slots is 2.5*d*. Estimate the maximum feed rate in rivets/sec if the efficiency with which rivets fall into the slots is 30% and the diameter of the rivet shanks *d* is 5 mm. (Note: The gate is at the bottom of the feeder body.)

17. A rivet feeder (external gate hopper) has a gate, 6.75-mm wide, through which the shanks of the rivets pass. The slots in the rotating inner sleeve are spaced at 15-mm intervals, and the gap between the body of the feeder and the inner sleeve is 2.5 mm. Estimate the maximum feed rate in rivets/min if the diameter of the rivet shank is 5 mm and, on the average, every third slot contains a rivet when the slots pass over the gate, which is located at the bottom of the feeder body.

18. A rivet feeder (external gate hopper) has a gate, 6-mm wide, through which the shanks of the rivets pass, and the diameter of the shank of the rivet is 5 mm. The rivets are tumbled within a rotating inner sleeve having slots to accept the rivet shanks that are just wide enough to accept one rivet. The gap between the inner sleeve and the body of the feeder is 2.5 mm, and the distance between the centers of the slots is 12.5 mm.

Estimate the maximum feed rate in rivets/sec if the efficiency with which rivets fall into the slots is 30%. (Note: The gate is at the bottom of the feeder body).

19. For an external gate hopper:
    a. Determine the maximum value of the gap h_g between the cylinder and the sleeve such that the cylindrical part (diameter D) cannot become jammed between the lower corner of the slot and the inner surface of the sleeve. Assume that the angle of friction for all surfaces is 30°.
    b. For these conditions and for a gate width equal to $3D/2$, find the maximum peripheral velocity v for the inner cylinder in terms of D and g.

20. An external gate feeder has an external gate 1.3*d* wide where *d* is the diameter of the cylindrical parts to be fed. The distance between the centers of the slots is 2*d* and the efficiency with which the parts are collected in the slots is 34%. The gap between the inner rotating sleeve and the external stationary body of the feeder is 0.6*d*.
    Derive expressions in terms of *d* and *g* for:
    a. The maximum peripheral velocity of the inner sleeve
    b. The corresponding maximum rotational speed (rpm) of the inner sleeve, if its diameter is 20*d*
    c. The corresponding feed rate (parts/sec).

If the diameter d is 0.125 in., find:

d. The rotational speed in rev/min
e. The feed rate in parts/sec

21. A centerboard hopper has a blade that is designed to reciprocate up and down along a vertical path. (Note: It is not pivoted).
    The track on the top of the blade is inclined at an angle of 30°, and it has a length of 200 mm. The blade is raised a total distance of 200 mm by a period of uniform acceleration followed by an equal period of uniform deceleration. The blade is lowered in the same manner.
    a. If the parts are not to leave the blade during deceleration, what is the minimum time to raise and lower the blade?
    b. If the coefficient of friction between the parts and the blade is 0.2, what is the minimum dwell period for all parts to slide off a full track?
    c. If the efficiency of parts selection is 30%, what is the maximum feed rate per minute for parts 20-mm long?

22. A centerboard hopper has a blade length of 262.5 mm and is designed to feed cylindrical parts end to end. The center of rotation (which is in line with the track) is 250 mm from the lower end of the blade track. The inclination of the track when the blade is in its highest position is 45°, and the coefficient of sliding friction between the parts and the track is 0.3. The blade is driven by a cam drive such that the raising of the blade is carried out by a period of uniform acceleration followed by an equal period of deceleration of the same magnitude. The blade then remains stationary to allow parts to slide into the delivery chute and is finally lowered in the same manner as it was raised.

If the efficiency with which parts 1-in. (25.4-mm) long are selected by the blade track is 50%, calculate the maximum feed rate possible with these parts (parts/sec) and the corresponding cycle time in seconds.

23. The blade of a centerboard hopper feeder oscillates vertically as shown in Figure P.23.
    a. For the condition in which the blade is full of parts, find the maximum deceleration of the blade so that parts will not lose contact with the track.
    b. Assume that the blade is raised 50 mm by accelerating at the value found in problem 23a, decelerates at this value for the next 50 mm, remains stationary to allow all parts to slide off the track, and is finally lowered in the same manner as it was raised. Find the total cycle time in seconds if the coefficient of friction between the parts and the track is 0.3.

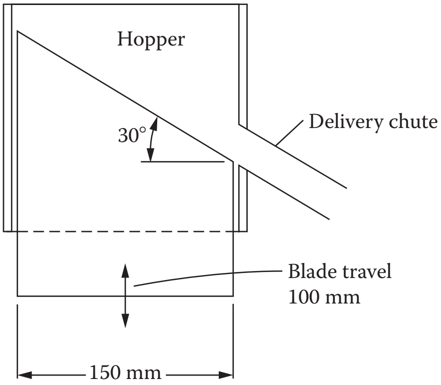


FIGURE P.23

c. Find the delivery rate (part/sec), assuming that the efficiency of part selection is 30% and that the parts are 10-mm long.

24. A centrifugal hopper has a diameter of 0.5 m and is designed to feed steel cylindrical parts 20-mm long and 5 mm in diameter. The wall of the hopper is steel and, to increase the feed rate, the base is coated with rubber.
If the coefficient of friction for steel/steel is 0.2 and for steel/rubber is 0.5, estimate:
a. The maximum possible feed rate for the hopper
b. The rotational frequency (rev/sec) that will give this feed rate

25. A centrifugal hopper has a diameter of 0.3 m and is designed to feed steel cylindrical parts 10-mm long and 4 mm in diameter. The wall of the hopper is steel and, to increase the feed rate, the base is coated with rubber.
If the coefficient of friction for steel/steel is 0.2 and for steel/rubber is 0.5, estimate:
a. The maximum possible feed rate for the hopper (parts/sec)
b. The maximum rotational frequency (rev/sec) that will give this feed rate

26. The part in Figure P.26 is to be fed and oriented by a double-belt feeder in the orientation depicted. A vision system has been devised that will detect the orientation desired and trigger a mechanism that will reject all other orientations. The belt feeder deposits unoriented parts onto the final delivery belt and then past the vision system at a rate of one part every 1.5 sec.

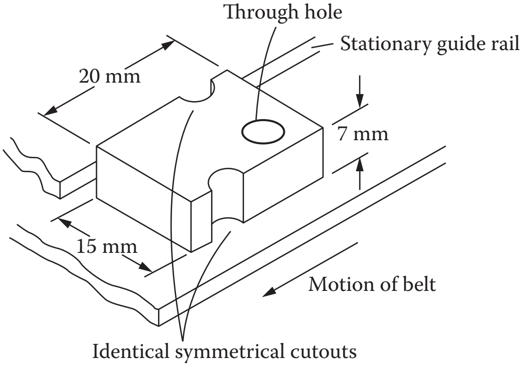


FIGURE P.26

Estimate the delivery rate of oriented parts, assuming that the coefficient of friction between the part and the guide rail is 0.2; neglect the effects of the cutouts and hole on the probabilities of natural resting aspects and orientations. Also, assume that the belts have "soft" surfaces. Use the graphs in Figure 3.55 and Figure 3.56, and assume that Figure 3.56 applies to a part passing along the guide rail of a belt feeder.

27. For a cup-shaped part fed in a vibratory-bowl feeder, the probability of feeding in orientation a, base down, is 45%, base leading (b) 20%, base trailing (c) 20%, and base up (d) 15%.

    A step reorients 5% of orientation a into c; 90% of orientation b into a; 10% of c into d and 30% into a; and 15% of orientation d into b and 20% into a.

    A scallop cutout rejects orientation d and finally a sloped track and ledge rejects orientations b and c.

    The diameter of the part is 20 mm and its length is 10 mm. Establish matrices for each orienting device and hence determine the orienting efficiency for the system. If the conveying velocity on the bowl track is 25 mm/sec, estimate the feed rate of oriented parts assuming these parts are touching as they enter the orienting system.

28. A V-shaped orienting device for a vibratory-bowl feeder is to be designed to orient truncated cone-shaped parts having a ratio of top diameter to base diameter of 0.8. Good rejection characteristics can be obtained when the half-angle of the cutout is 45°. Determine the maximum and minimum distances from the bowl wall to the apex of the cutout (expressed as a ratio of the part base radius) for which all the parts on their tops will be rejected and all the parts on their bases will be accepted. Assume that the parts never leave the track during feeding.

29. A vibratory-bowl feeder is to feed cylindrical cup-shaped parts. The track is to be designed such that only four feeding orientations of the part are possible:
   a: Part feeding on its base (27%)
   b_1: Part feeding on its side, base leading (35%)
   b_2: Part feeding on its side, top leading (35%)
   c: Part feeding on its top (3%)

The part has a length-to-diameter ratio of 1.13, and the orienting system comprises three devices:

1. A step that does not affect 49% of the parts in orientation a and that reorients 100% of b_1, 38% of b_2, and 80% of c to orientation a
2. A scallop cutout that rejects all the parts in orientation c
3. A sloped track and ledge that rejects all parts in orientations b_1 and b_2

If the input rate of parts to the orienting system is 2.5/sec, what will be the output rate of oriented parts from the system?

30. A part that is to be fed and oriented in a vibratory-bowl feeder has five orientations (a, b, c, d, e) on the bowl track. The orienting system consists of three devices. The first is a wiper blade that rejects all the parts in orientation e; the second is a step that reorients 20% of those in orientation a to orientation b, 10% of those in b to orientation c, 50% of those in c to orientation a, and 80% of those in d to orientation a and the third is a scallop cutout that rejects all parts not in orientation a. Write the matrices for each device and thereby calculate the efficiency of the system if the initial distribution of orientations is as follows:

$$a = 0.2 \quad b = 0.25 \quad c = 0.4 \quad d = 0.1 \quad e = 0.05$$

What would the efficiency of the system have been if no step had been included?

31. Rectangular prisms are to be fed and oriented in a vibratory-bowl feeder. The two orienting devices employed are a wiper blade and a narrowed track. The probabilities of the important orientations and the dimensions of the prisms are shown in Figure P.31.
   a. Construct matrices for the wiper blade and narrowed track and, hence, find the system matrix.
   b. By multiplying the system matrix and the orientation matrix, find the efficiency of the orienting system.
   c. Estimate the feed rate of oriented parts (parts/sec) if the conveying velocity is 100 mm/sec and if the parts are contacting each other as they enter the system.

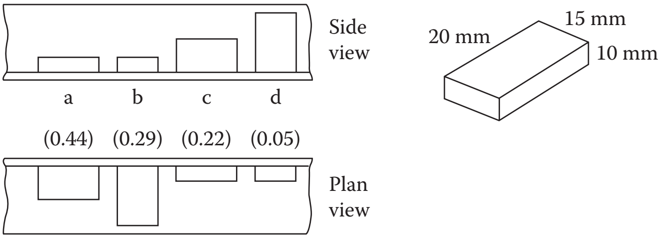
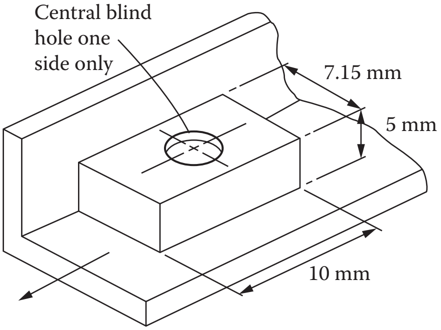


FIGURE P.31

32. The part shown in Figure P.32 is to be oriented and delivered using a vibratory-bowl feeder. The orienting devices to be used are (1) a wiper blade, (2) a narrowed track, and (3) a scallop cutout.
    a. Estimate the probability of the delivery orientation.
    b. Estimate the feed rate of oriented parts if parts enter the orienting system at 1/sec on average.



Parts to be delivered in orientation shown

FIGURE P.32

33. A vibratory-bowl feeder orienting system is designed to orient a part that has four orientations on the bowl track. The first device is a step whose performance can be represented by the following matrix:

$$\begin{array}{c} \\ a \\ b \\ c \\ d \end{array} \begin{array}{c} \begin{array}{cccc} a & b & c & d \end{array} \\ \begin{bmatrix} 0.49 & 0.51 & 0 & 0 \\ 1.0 & 0 & 0 & 0 \\ 0.28 & 0.02 & 0.3 & 0.4 \\ 0.80 & 0.1 & 0.1 & 0 \end{bmatrix} \end{array}$$

The remaining devices are designed to reject orientations *b, c,* and *d.*

Determine the feed rate of oriented parts if the input rate to the system is 2.5/sec and if the input distribution of orientations is

$$\begin{array}{cccc} a & b & c & d \\ [0.27 & 0.35 & 0.35 & 0.03] \end{array}$$

Also, estimate the effect on this performance if a further identical step is added to the beginning of the system.

34. Figure P.34 shows the orientations of a cup-shaped part that is to be fed by a vibratory-bowl feeder. The orientation system consists of a step (for which the performance matrix is given) followed by a scallop that rejects all *d*s and a sloped track and ledge that rejects all *b*s and *c*s. The probabilities of the initial orientations *a, b, c,* and *d* are 0.45, 0.25, 0.25, and 0.05, respectively.

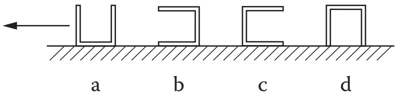
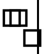


FIGURE P.34

a. What is the efficiency η of the orienting system?
b. What would the efficiency be if the step was not used?



$$\begin{array}{c|cccc|} & a & b & c & d \\ a & 1 & 0 & 0 & 0 \\ b & 0.1 & 0.9 & 0 & 0 \\ c & 0.8 & 0 & 0.1 & 0.1 \\ d & 0.5 & 0 & 0.5 & 0 \end{array}$$

35. The rectangular prismatic part is to be fed and oriented in a vibratory-bowl feeder as shown in Figure P.35. Determine the efficiency (η%) of this orienting system. Assume a hard track surface, and assume that the coefficient of friction between the bowl wall and the part is 0.2.

36. The part shown in Figure P.36 is to be fed and oriented by a vibratory-bowl feeder in the orientation depicted. A television system has been devised that will detect the orientation desired and trigger a mechanism that will reject all other orientations. What will the feed rate be? Assume that the coefficient of friction between the part and the bowl wall is 0.2. Assume that the conveying velocity of the parts on the bowl

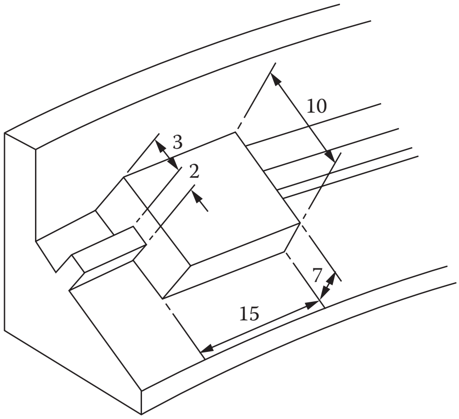


FIGURE P.35

track is 20 mm/sec, and neglect the effects of the cutouts and hole on the probabilities of natural resting aspects and orientations. Also, assume a hard surface on the bowl track.

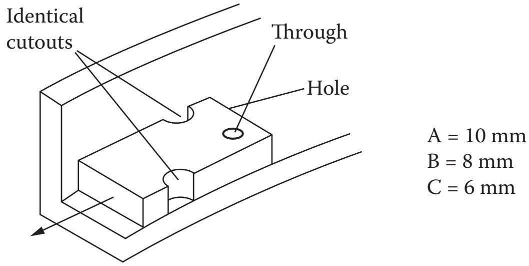


FIGURE P.36

37. Figure P.37 shows a U-shaped metal part that is to be finally oriented by a projection from the wall of a metal vibratory-feeder bowl.

Find:

a. The probabilities of each of the orientations on the bowl track shown in the figure
b. The efficiency of the orienting system if the projection device shown is preceded by a step in the track that reorients 10% of parts in orientation *c,* 20% of *d,* and 20% of *e,* all equally divided into orientations *a* and *b*
c. The feed rate in parts/min if parts enter the system at a rate of 30 parts/min

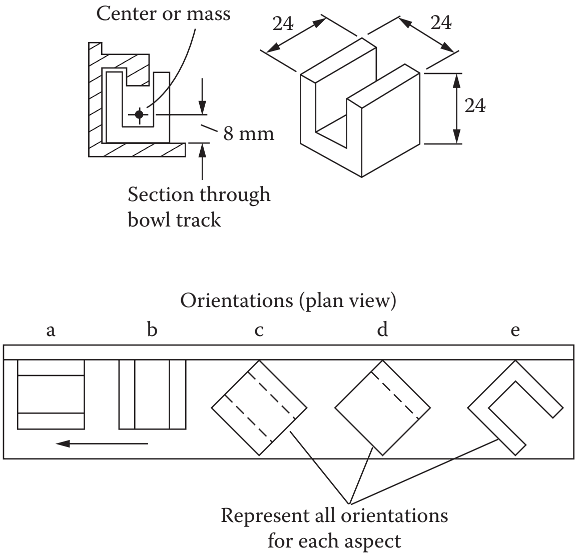


FIGURE P.37

38. The metal part shown in Figure P.38 is to be fed and oriented in a vibratory-bowl feeder. The first device is a wiper blade set to reject orientations *c–f*. The second device is a scallop cutout that rejects all parts in orientation *b* and 7% of the parts in orientation *a*.

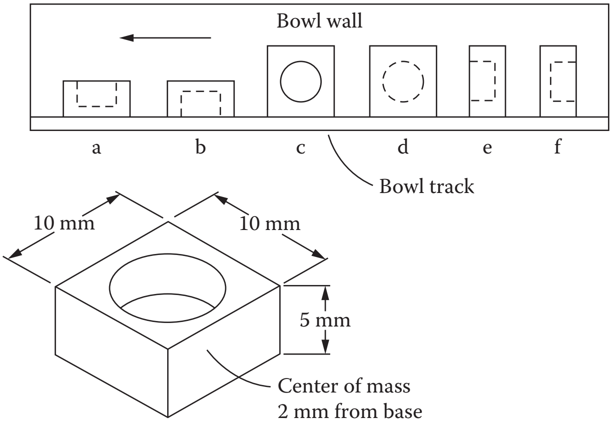


FIGURE P.38

 a. Set up matrices for each device and, by multiplication, obtain the system matrix.

b. From the graphs in the text, determine the complete input distribution matrix (assume μ = 0.2).
c. Find the efficiency for the system.

39. An orienting system for a vibratory-bowl feeder is designed to feed the part shown in Figure P.39. The important orientations are labeled *a, b, c,* and *d*. The first device, a wiper blade, rejects parts in orientation *d*; then, a narrow track rejects orientation *c*; and, finally, a scallop cutout rejects orientation *b*. Assuming metal parts on a metal track, estimate the feed rate of oriented parts, assuming a mean conveying speed of 20 mm/sec and a coefficient of friction of 0.2. Also, assume that parts enter the orienting system touching each other.

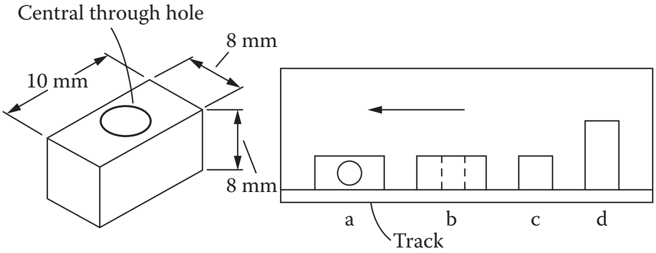


FIGURE P.39

40. A straight feed track was inclined at an angle of 30°. How long would it take to deliver a part 15-mm long from rest if the coefficient of friction is 0.5?

It was desired to continuously deliver the parts at a rate of 10/sec so a vibrator was applied to the track to provide a parallel vibration at 120 Hz. What vibration amplitude (mm) would be required? (Use the equation for the mean conveying velocity in the text).

41. A gravity feed track consists of a straight section of track inclined at an angle of 45°, followed by a section of constant radius 10 in. (254 mm), which is followed by a straight horizontal section 5 in. (127 mm) in length. The complete track is arranged in a vertical plane and is to be used in the feeding of parts 0.5 in. (12.7 mm) in length.

Determine the minimum vertical height (in inches or millimeters) of the top of the column of parts above the inlet to the workhead for feeding to occur if the coefficient of friction between the parts and the track is 0.4.

42. a. A straight gravity feed track inclined at an angle of 15° was found to perform inadequately. A 60-Hz vibrator was attached to the track

to improve its performance, and it could achieve a parallel track amplitude of vibration of 0.14 mm. If the coefficient of friction between the parts and the track was 0.3, what would be the velocity of the parts down the track?

b. Aluminum parts are to be fed on an aluminum, horizontal-delivery gravity feed track. The track has a straight portion inclined at an angle of 45°, followed by a curved portion having a radius of 250 mm and, finally, a horizontal straight portion 50 mm in length. If the parts are 10 mm in length, what will be the minimum delivery time for an escapement placed at the outlet to the track if the height of the column of parts is maintained at 250 mm above the outlet? Assume that the coefficient of friction is 0.3.

43. A straight gravity feed track is inclined at 15° and feeds 10-mm-long parts directly into a slide escapement, which is also inclined at 15°. What is the maximum rate at which the slide escapement can operate? Give your answer in cycles/min. Assume that the coefficient of dynamic friction between the parts and the track is 0.26 and that the track is full of parts. It was desired to increase the maximum speed of the escapement by applying a vibration to the track parallel to the track at a frequency of 120 Hz. Using the empirical expression in the text, find the vibration amplitude to give a conveying velocity of 100 mm/sec.

44. The cost of certain screws C is found to be given by

$$C = 10 + 0.01/x \text{ cents}$$

where x is the ratio of faulty screws to acceptable screws. A machine is to be built to assemble 20 such screws (one at each station) into an electrical terminal strip. An assembly worker costing \$15/h will be employed to load the terminal strips (costing 50 cents each), and an engineer costing \$20/h will correct machine faults. The rate for the machine (excluding personnel) is estimated to be \$50/h.

a. If all faulty parts cause a machine stoppage and if it takes 20 sec to correct each fault, find the *minimum* cost of each complete assembly on an indexing machine working on a 4-sec cycle.

b. If a robot costing \$40/h could be used to feed, orient, and insert the terminal strips (quality level $x = 0.015$) and if the downtime for each faulty terminal strip was 40 sec, what would the new *minimum* cost be?

45. An indexing assembly machine has ten stations, and the total cost of running the machine (including operators and overheads) is \$0.02/sec. The quality levels x of the parts at each station and the proportions of defective parts that cause a machine stoppage are as shown in the

following table. Assume that the time T to correct a machine fault is 30 sec on average and that operator assembly costs are \$0.25/assembly. Assume also that the cost of disassembling unacceptable assemblies is \$0.80 on average and that the machine has a memory pin system to detect those defective parts that do not stop the machine.

TABLE P.45
Part Quality Levels

Station	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
x, %	0.12	1.3	1.4	0.5	2.3	0.3	1.6	0.25	0.25	3.6
m	1.0	0.5	1.0	1.0	0	0.5	0.5	1.0	1.0	1.0

At what cycle time t (sec) must the machine be operated so that assembly costs will be the same as those for manual assembly?

46. A ten-station indexing assembly machine is fully automated, and each automatic workhead incorporates a memory pin system so that when a fault is detected, the machine continues to run but no further work is carried out on the assembly containing the fault. If the cycle time of the machine is 5 sec and, at each station the ratio of unacceptable to acceptable parts is x%, calculate approximately the production rate of acceptable assemblies/min when $x = 1.5$.

Given that the total running cost of the machine is \$1/min, it takes an average of 40 sec to dismantle an unacceptable assembly, operator costs are \$0.4/min, and the cost of each part used by the machine is given by A + B/x where $A = B =$ \$0.004/part, calculate the number of operators required to dismantle the incomplete assemblies and the total cost of the product. If the parts quality is now changed to the optimum value, determine the optimum and the new total cost of the product.

47. A five-station indexing assembly machine works on a cycle time of 3 sec, and the ratio of unacceptable to acceptable parts used at each station is 0.02. The average time to correct a fault at each station for a machine that stops in 20 sec, and the average time taken to dismantle each part of a faulty assembly on a machine that incorporates a memory pin system is 30 sec. The total running cost of the machine is \$0.40/min, and the total cost of each assembly worker used on the machine is W_a cents/min.

Determine:

a. The production rate and assembly cost per assembly for a machine that stops when a fault occurs

b. The production rate and assembly cost per assembly for a machine that incorporates the memory system
c. The value of W_a for which the cost per assembly is the same for both types of machine

Assume that the machine that stops requires only one operator and calculate the extra assembly workers required on the machine that has a memory pin facility.

48. A five-station indexing assembly machine has a cycle time of 3 sec. The quality levels of the parts supplied to the workheads is 1.1, 2.3, 0.6, 1.5, and 0.2%, respectively. The average time taken to correct a fault and restart the machine is 30 sec. Assuming that every defective part will cause a machine fault, calculate:
    a. The percentage downtime for the machine
    b. The average production rate (assemblies/min)

If the cost of operating the machine (including overhead) was \$20/h, what maximum amount could be spent over a 2-year period to eliminate the defective parts fed to station 2. (Assume 50 weeks working at 40 h/week.)

49. A five-station indexing assembly machine has a cycle time of 5 sec. The quality level of the parts supplied to the workheads is 1.1, 2.3, 0.6, 1.5, and 0.2%, respectively. The average time taken to correct a fault and restart the machine is 60 sec. Assuming that every defective part will cause a machine fault, estimate:
    a. The percentage downtime for the machine
    b. The average production rate (acceptable assemblies/min)

Repeat the calculations assuming that only half of the defective parts causes a machine fault while the other half spoils the assembly.

50. A rotary indexing assembly machine has six stations. Station 1 involves the manual removal of the completed assembly and the manual loading of the base part of the assembly. The remaining stations are all automatic. These involve the assembly of three pins having quality levels of 1.4% defectives and a cover having a quality level of 0.9% defectives. At the last station, two holding-down screws are inserted, having a quality level of 2% defectives.

If the machine cycle time is 3 sec and the downtime caused by one defective part is 30 sec, determine:

a. The percentage downtime for the machine
b. The average production rate in assemblies/min

If the total machine rate is \$16/h (including operator costs and overheads), would it pay to spend \$0.20/100 screws to improve their quality level to 1% defectives?

51. An indexing machine has 12 automatic stations. At stations 1–7, the quality level of the parts is 0.015 defectives; at station 8, the quality is 0.025, and at the remaining stations the quality is 0.007. One part is assembled at each station, and each faulty part causes machine downtime of 40 sec. The machine was designed to produce 10 assemblies/min but, unfortunately, the designers neglected to take into account the downtime due to faulty parts.

Estimate:

a. The production rate actually achieved
b. The percentage downtime
c. The machine cycle time needed to achieve the originally planned assembly rate if the downtime due to each fault can be reduced to 20 sec.

52. You have purchased a 3-sec cycle, 20-station indexing assembly machine and, after debugging is complete, the downtime due to faulty parts is 57%. Running costs for the machine are estimated to be \$20/h for the machine and \$30/h for the operator. You are considering converting the machine into two 10-station indexing machines operating at the same speed and have estimated that the cost of conversion will add \$5/h to the running costs. In both situations, the average time to clear a fault and restart the machine is 30 sec. What will be the new downtime and the projected savings or losses due to the conversion? Express the answers in cents per assembly, and assume that the quality levels for all the parts are the same and that all faulty parts cause a machine stoppage.

53. A three-station, free-transfer mechanized assembly machine has a cycle time of 4 sec. At each station, the ratio of defective to acceptable parts is 1:150, and the time taken to correct a fault at any station is 10 sec. Assuming that all stoppages are due to faulty parts, determine the production rate of the machine for equal buffer spaces between each station for 0, 1, 2, 3, 4, and 5 work carriers.

If the total cost M of running the machine for 1 min is given by

$$M = 0.8 + 0.009b$$

where b is the buffer space between each station, determine the assembly cost per assembly for each of the conditions specified above and, hence, show that an optimum value of b exists for which the assembly costs are minimum.

54. A 24-station indexing machine has a memory system so that only 40% of the faulty parts cause a machine stoppage. One technician is assigned to correct stoppages and to refill the part feeders when necessary. The machine costs $28K per station including workheads, transfer device, feeders and work carriers.
    a. Estimate the total machine and operator rate if the technician costs $40/h including overheads, the equipment payback is 2 years with 2-shift working and equipment overheads are 135%.
    b. Estimate the proportion of downtime on the machine due to stoppages only if the average quality level of parts is 0.008, the average downtime per fault is 30 sec and the workhead cycle time is 6 sec.
    c. Estimate the cost of assembly in cents if the average cost of dealing with each incomplete assembly is $1.20.
    d. If it takes 90 sec to deal with each incomplete assembly, how many personnel will be required to perform this task?

55. A 24-station closed-loop nonsynchronous assembly machine has five buffer spaces between each station and each space costs $4.5K with each station and associated controls and feeders costing $16.5K. The pallets cost $1.5K each, and there are three pallets per station.

Two technicians are assigned to correct workhead stoppages caused by faulty parts and to refill the part feeders when necessary.

  a. Estimate the total machine and operator rate in $/h if each technician costs $40/h including overheads, the equipment payback is 2 years and 2-shift working and equipment overheads are 135%.
  b. With the aid of Equation 6.16 and Equation 6.19 in the text, estimate the proportion of downtime on the machine if the average quality level of parts is 0.008, the average downtime per fault is 30 sec and the workhead cycle time is 6 sec.
  c. Estimate the cost of assembly in cents.
  d. For what proportion of their time will the technicians be engaged in correcting faults?

56. A six-station rotary indexing machine performs assembly tasks as follows:

Station	**Operation**	**Faulty Parts (x)**
1	Manually load base	0.02
2	Automatically assemble plate	0.005
3	Automatically insert 2 screws	0.01
4	Automatically assemble clip	0.007
5	Automatically insert 1 screw	0.015
6	Manually place cover and remove assembly	0.008

a. If the average time taken to correct a fault is 50 sec and the machine cycle time is 5 sec, estimate the proportion of downtime if all the faulty parts cause a machine stoppage at the automatic workstations.
b. What is the average production rate of assemblies per minute?
c. If the machine speed were increased to give a 2-sec cycle, what would be the new proportion of downtime?
d. What would be the new production rate?

57. A nonsynchronous assembly machine has 50 stations each with a cycle time of 5 sec. The average downtime to correct a workhead stoppage is 25 sec and the proportion of parts causing stoppages is 80 in 10,000.
    a. What is the optimum buffer size between stations according to the analysis in the text?
    b. What is the average production time per assembly?
    c. How many technicians would be required (rounded up to the nearest integer) to correct faults?
    d. The total cost of the machine is \$2.5M with a 5-year payback and two-shift working. The rate for one technician is \$20/h. If 100% overheads are applied to equipment depreciation and technician rate, what is the total rate for the machine and technicians?
    e. What is the cost of assembly per assembly in cents?
    f. If the average time for manual assembly per part is 8 sec and the rate for one assembly worker is \$30/h including overheads, what would be the cost of manual assembly?

58. Compare the average cost of assembly per assembly using an in-line indexing machine and a nonsynchronous machine. Thirty parts (one per station) are to be added automatically and, on average 0.8% of the parts are faulty — each one causing a stoppage. The cycle is 5 sec and the average downtime per fault is 25 sec. Each machine would have two assembly workers (rate \$20/h), one to place the base part on the machine and the second to remove completed assemblies at the other end. The rate for technicians who correct faults is \$40/h.

The indexing machine costs \$25,000 per station, and the nonsynchronous machine costs an extra \$10,000 per station for buffers, controls and work carriers.

The machines are to be amortized over 3 years, working two shifts and equipment overheads are 100%. Overheads are already included in the worker rates quoted.

59. A six-station rotary indexing machine cost $160,000 and is to be used on a 2-shift basis with a payback period of 2 years. Overheads for the machine are 100%. To run the machine requires one assembly operator and one supervisor costing the company $30,000 and $50,000 per year, respectively. The machine cycle time is 3 sec. The average downtime caused by one faulty part is 30 sec and the proportion of faulty parts at the various stations is as follows:

Station	**1**	**2**	**3**	**4**	**5**	**6**
Proportion of Faults	0.01	0.005	0.005	0.02	0.01	0.015

   a. What is the total cost of operating the machine in dollars/hour?
   b. What is the proportion of downtime on the machine?
   c. What is the average production in assemblies per minute?
   d. What is the total cost of assembling each assembly in cents?

Note: 1 shift-year = 2000 hours

60. Screws used in an assembly cost 5 cents each when the quality level ratio is 0.01; they cost 7.5 cents each when the quality is 0.005. Assume that the relation between quality level x and Cost C is given by

$$C = A + B/x$$

where A and B are constants.

Four screws are to be inserted on a rotary indexing machine. At the first station, the base part and the cover are loaded manually. At the second station two screws are inserted automatically and, at the third station, the two remaining screws are inserted automatically. At the fourth station, the complete assembly is removed by the same operator working at station one.

The cost of the operator is $30/h and a technician costing $40/h is required to correct faults. Machine cycle time is 3 sec, and the average fault correction time is 30 sec. The cost of the base part and cover is $2.16 and the rate for the machine is $30/h. Overheads have already been included in the personnel and machine rates.

   a. What is the optimum quality level for the screws if all defective screws cause a machine stoppage?
   b. What is the average production time per assembly?
   c. What is the proportion of downtime for the machine?

d. Using optimum quality for the screws, find the minimum cost of the product.

61. A five-station free-transfer machine has equal buffer spaces between workstations that can accommodate four work carriers each.

The cycle time for each workstation is 4 sec, the ratio of defective to acceptable parts at each station is 0.015, and the time to correct a workstation stoppage due to a faulty part is 20 sec.

a. Using the appropriate tables and equations in the text, determine the machine downtime. Hence or otherwise determine the average production rate in assemblies per minute.
b. What would be the downtime and production rate for a five-station indexing machine producing the same assembly?
c. If the free-transfer machine costs 20% more to operate than the indexing machine, which machine would yield the lowest assembly costs?

62. A feasibility study is to be conducted for the automatic assembly of 35 parts having an average ratio of fully parts that would cause a stoppage of 0.006 with an average fault correction time of 20 sec. The following equipment costs in thousands of dollars are to be used:

Cost of one workhead — 10
Cost of per station of indexing machine — 10
Cost of per station (including buffers) of nonsynchronous machine — 25
Cost of one feeder — 7
Cost of one work carrier — 1.5

Also, the cost of an assembly worker is 30 $/h and the cost of one technician is 50 $/h.

a. Estimate the proportion of downtime, and the cost of assembly (cents) for an indexing machine with a cycle time of 3 sec.
b. Estimate the proportion of downtime and the cost of assembly (cents) for a nonsynchronous machine with five buffers between workheads and with a cycle time of 4 sec.

In each case, assume 2-shift working, a payback of 3 years, 100% overhead on equipment and labor, two assembly workers on each machine and the required number of technicians.

63. An assembly operation involves ten operations. No operations can be carried out until operation 1 is complete. Operation 10 cannot be carried

out until all other operations are completed. Operation 9 cannot be carried out until operations 7 and 8 are complete. Operations 5, 6, and 7 cannot be carried out until operation 3 has been completed. Operation 8 cannot be carried out until operation 4 is complete. Draw a precedence diagram for this assembly process.

64. Construct a precedence diagram for the 12 parts of the box-and-lid assembly shown in Figure P.64. Assume that the first operation is to place the box (part 1) in the work fixture.

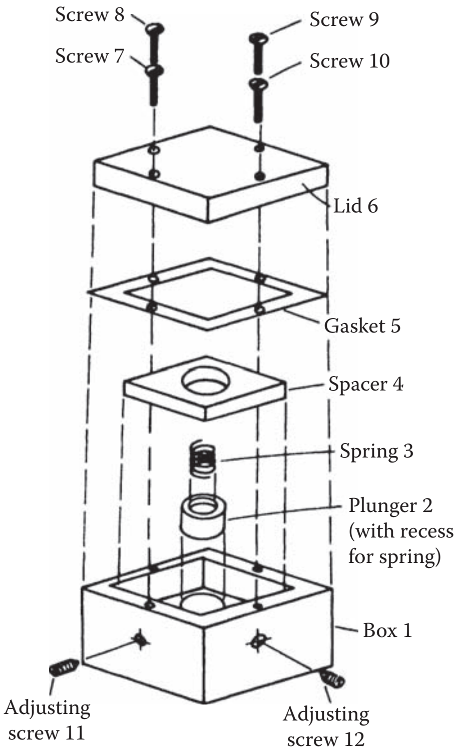


FIGURE P.64

65. A feasibility study is to be made for the automatic assembly of three components (Figure P.65) on an indexing machine that would operate at 1 cycle/sec, with an average downtime due to stoppages of 30 sec. Preliminary studies indicate that the screw has a quality level of 1.5% completely defective. The plastic base has 2.0% defective, but only 0.5% would prevent assembly of the screws; the remainder are cracked or have unacceptable appearance. The metal clips have 1.0% defectives where the screw cannot pass through the hole.

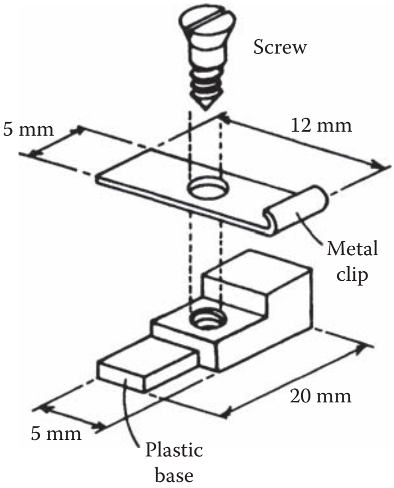


FIGURE P.65

The estimated total rate for the assembly machine is \$23/h, including one operator and overhead. It is possible to improve the quality levels of the screw and clip to 0.5 and 0.2%, respectively, by means of automatic inspection machines. How much would you be prepared to spend on these machines to reduce stoppages on the assembly machine? Neglect the cost of dealing with faulty assemblies produced by the machine, and assume a payback period of 4000 h and 100% overhead for equipment.

66. Estimate the manual assembly time and the design efficiency for the assembly shown in Figure P.66. The assembly procedure is as follows:
    1. The retainer bush is placed in the work fixture.

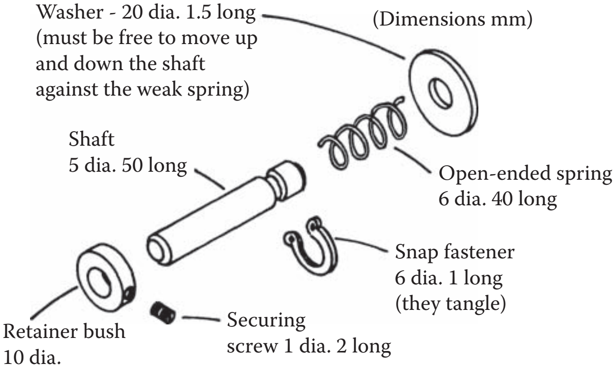
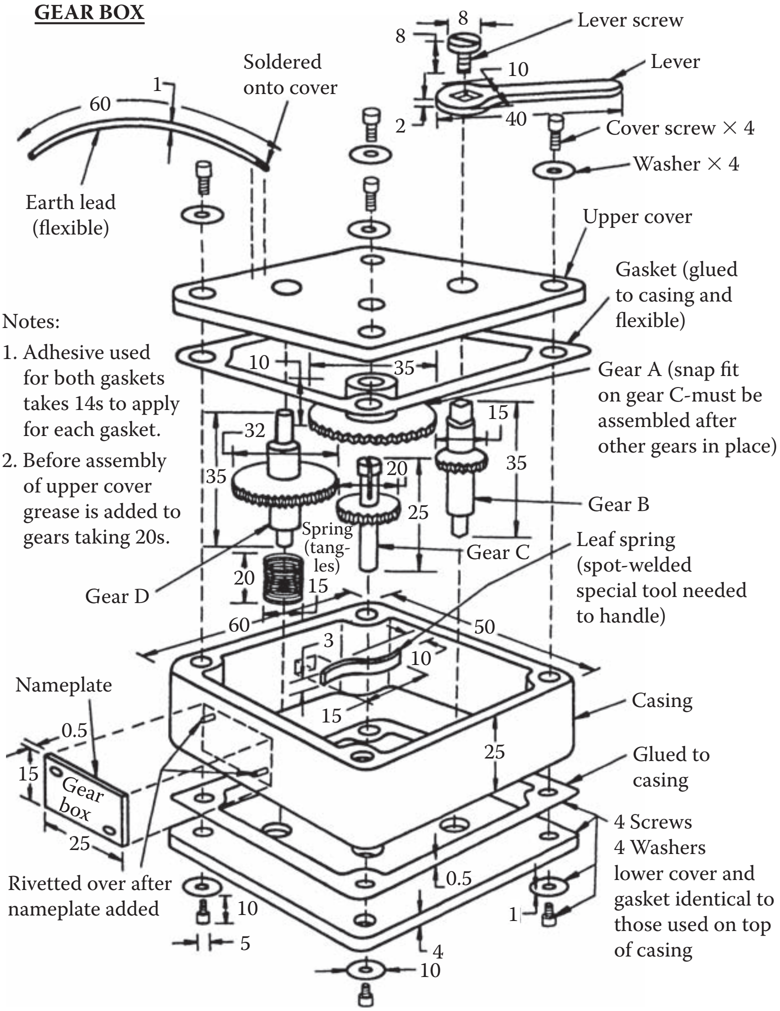

Washer - 20 dia. 1.5 long (must be free to move up and down the shaft against the weak spring)
(Dimensions mm)
Shaft 5 dia. 50 long
Open-ended spring 6 dia. 40 long
Snap fastener 6 dia. 1 long (they tangle)
Retainer bush 10 dia.
Securing screw 1 dia. 2 long

FIGURE P.66

2. The shaft is inserted into the bush.
3. The securing screw is inserted into the bush and is difficult to align and position.
4. The spring tangles severely and, when separated from the others, is dropped onto the shaft.
5. The washer is inserted onto the shaft and then held down while the snap fastener is positioned using a standard grasping tool.

67. Analyze the gear-box assembly shown in Figure P.67 for manual assembly.


GEAR BOX
8
8
Lever screw
10
Lever
2
40
Cover screw × 4
Washer × 4
Soldered onto cover
1
60
Earth lead (flexible)
Upper cover
Gasket (glued to casing and flexible)
10
35
Gear A (snap fit on gear C-must be assembled after other gears in place)
15
32
35
20
35
25
Gear B
Spring (tangles)
Gear C
Leaf spring (spot-welded special tool needed to handle)
20
15
Gear D
60
50
3
10
15
Nameplate
0.5
15
Gear box
25
Casing
25
Glued to casing
4 Screws
4 Washers
lower cover and gasket identical to those used on top of casing
0.5
Rivetted over after nameplate added
10
5
1
4
10

Notes:

1. Adhesive used for both gaskets takes 14s to apply for each gasket.
2. Before assembly of upper cover grease is added to gears taking 20s.

FIGURE P.67

Obtain the estimated assembly time, assuming that none of the parts are easy to align and position. Also, obtain the theoretical minimum number of parts, assuming that the springs and the earth lead must be of different materials from the remaining parts. Suggest a redesign for the gear box, assuming that two screws only are needed to secure the upper cover, and estimate the assembly cost for the redesign.

68. Analyze the terminal block shown in Figure P.68 for manual assembly. Give the estimated assembly time and the design efficiency.

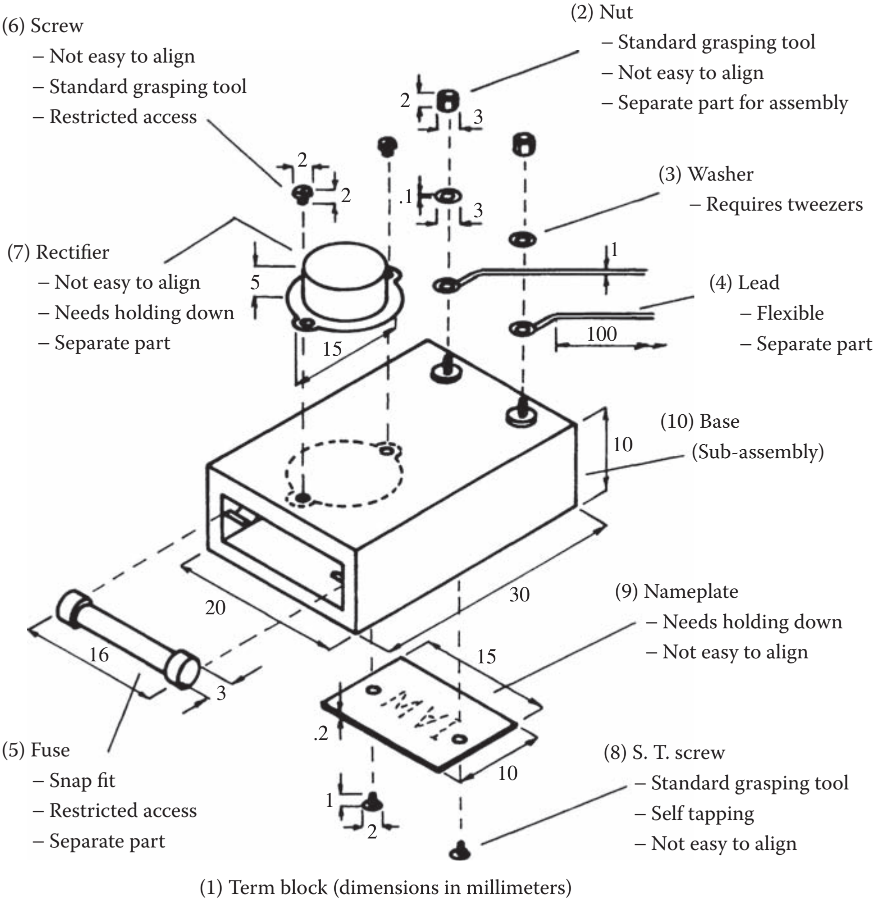


FIGURE P.68

69. Consideration is being given to the purchase of an automatic DIP insertion machine that would be fully occupied inserting 26 14-pin DIPs into a PCB. At present, the DIPs are inserted manually. Estimate the breakeven total batch size for the boards if one setup is used for

the batch. Include the costs of rework and the cost (150 cents) for a replacement component when rework is carried out. The assembly worker rate is \$36/h, including overheads.

70. A wave-soldered PCB has 25 axial components of 15 types, 32 radial components (2 leads) of 4 types, 2 radial components (3 leads) of 1 type, 14 DIPs (16 pins) of 10 types, and 1 connector (SIP) with 20 pins.

All the components are manually inserted, but the company is interested in the probable savings if a radial inserter for two lead radials, and a DIP inserter is available.

Estimate the total cost of manual insertion and the savings to be obtained through the use of the auto inserters. Assume a total life volume (total batch size) of 50, two setups, and an assembly worker rate of \$45/h. Neglect the costs of loading the board into the fixture, of wave-soldering, and of replacement components.

71. A PCB has 28 14-pin DIPs of 6 types and 32 axial (VCD) components of 10 types inserted automatically. Manual insertion of 6 can-type components with 3 leads each follows.
    The board is wave-soldered (2 boards per panel).

Estimate the total assembly cost per board if the batch size is 200 with one setup. Use the equations and data in the textbook and include the cost of rework. Assume an assembly worker rate of \$30/h and an average component replacement cost of \$1.00.

72. Parts in the form of truncated cones have a base diameter of 30 mm, a top diameter of 25 mm, and a height of 20 mm. They are to be fed and oriented using a vibratory-bowl feeder with a V-cutout orienting device having a half angle of 45° and mounted on the horizontal portion of the track. Using the *Handbook of Feeding and Orienting Techniques for Small Parts*, in Appendix D, determine:
    a. The three-digit geometric part code.
    b. The conveying velocity in mm/sec if the bowl frequency is 60 Hz, the bowl spring angle is 65°, the bowl diameter is 200 mm, the radius at which the springs are positioned is 75 mm and the horizontal peak-to-peak amplitude at the bowl wall is 0.533 mm.
    c. The maximum acceptable distance the part can hop during each vibration cycle in mm.
    d. The estimated effective distance the part hops during each vibration cycle in mm.
    e. The recommended distance from the apex of the V cutout to the bowl wall.

73. The metal part in Figure P.73 is to be fed and oriented on a “soft” track using a wiper blade and the projection and narrow track shown.

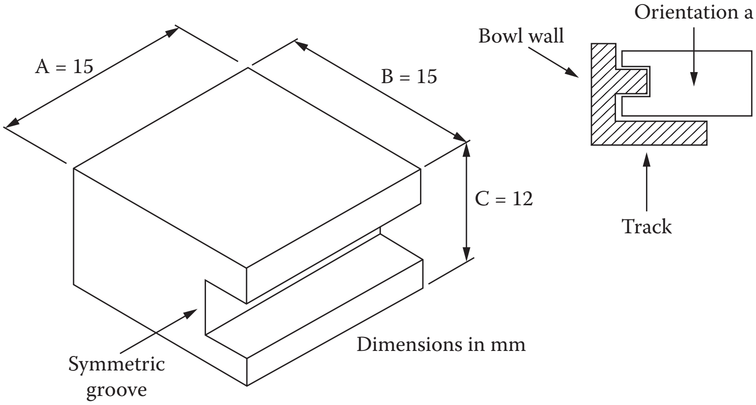


FIGURE P.73

What is the three-digit part code? Determine the probability of orientation a (the feeding orientation) and, hence, estimate the feed rate in parts/min when the conveying velocity is 20 mm/sec. The coefficient of friction is 0.3. (Use the graphs on page 82 and page 84 of the text to obtain the probability of orientations neglecting the effect of the slot).

74. The U-shaped part shown in Figure P.74 is to be automatically fed and oriented. Using the *Handbook of Feeding and Orientating Techniques for Small Parts* in Appendix D, find the three-digit code and estimate the feed rate that could be obtained using:
   a. A 450-mm-diameter vibratory-bowl feeder operating at 60 Hz, with a spring angle of 70° and where the springs are mounted at a radius of 100 mm. Assume that the amplitude of vibration is adjusted so that the parts on the last horizontal section of the track are on the verge of hopping.
   b. A tumbling-barrel feeder where the conveying velocity on the vibratory rail is 30 mm/sec.

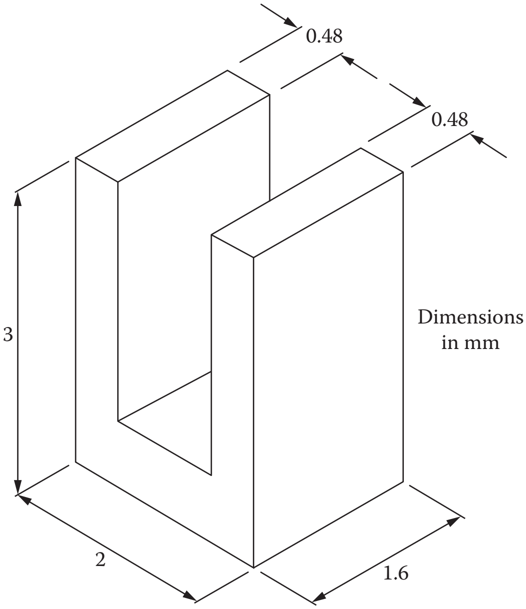


FIGURE P.74

Appendix A

Simple Method for the Determination of the Coefficient of Dynamic Friction

Every student of physics or engineering is aware of the difficulties in obtaining an accurate measurement of the coefficient of dynamic friction between two surfaces. The simple methods normally employed in laboratory demonstrations, methods that everyone is familiar with, are usually unsatisfactory and yield results with large random errors. The improvement in accuracy that can be obtained through repeated measurement is not usually feasible because of the time-consuming adjustment of the inclination of a plane or the adjustment of the load applied to a slider.

An experimental device that will drive a loaded slider across a surface and record the resulting frictional force is necessarily elaborate and expensive, and generally justifiable only when research into the frictional behavior of sliding surfaces is undertaken.

The method described here [1] is not intended for this kind of work but is suggested as a replacement for simple undergraduate laboratory experiments on friction or for a rapid measurement of the coefficient of dynamic friction, which is so often desirable in any engineering problem involving relative motion between surfaces.

A.1 THE METHOD

Figure A.1 shows the experimental setup where the slider (1) and the straightedge (2) are placed on a sheet of paper on a horizontal and reasonably flat surface such as a drafting board. A means is provided for constraining the straightedge to move in a straight line over the surface in a direction inclined at an angle θ to the edge itself. This can readily be arranged using a T square and triangle.

As the straightedge is moved at reasonably uniform speed in the direction of arrow *A* in Figure A.1, the slider moves in the direction of arrow *B*, a direction that (as will be shown later) depends only on the coefficient of sliding friction

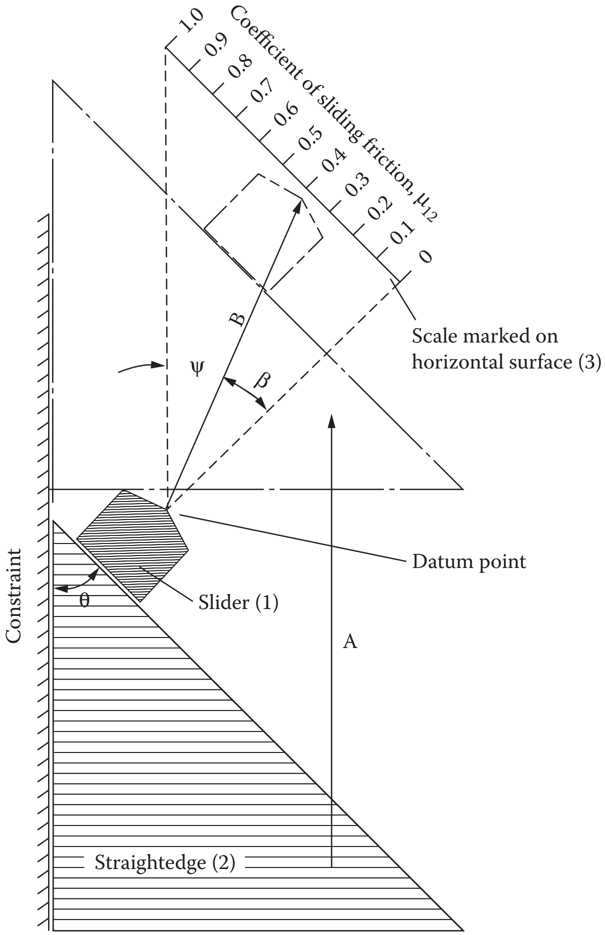


FIGURE A.1 Apparatus for determination of coefficient of dynamic friction. (From Boothroyd, G., Simple Method for the Determination of the Coefficient of Sliding Friction, *Bulletin of Mechanical Engineering Education*, Vol. 9, 1970, p. 219. With permission.)

between the slider and the straightedge and the angle θ. Thus, with the appropriate scale and datum point marked on the horizontal surface, the slider may be moved from the datum point to the scale and the coefficient of friction read off directly.

It will be appreciated that, with this method, repeated measurements can be made rapidly, and a precise determination of the required coefficient of friction can thus be obtained.

The scale marked on the horizontal surface must be appropriate to the chosen angle θ between the straightedge and the direction of its motion. For conditions in which the coefficient of friction lies between zero and unity, a convenient scale is obtained when θ is 45° (Figure A.1). For coefficients of friction greater than unity, a smaller angle of θ must be employed.

A.2 ANALYSIS

The horizontal forces acting on the slider (1) as the straightedge (2) is moved relative to the surface (3) are shown in Figure A.2. The frictional force between the slider and the surface acts in opposition to the direction of motion of the slider across the surface. This direction is inclined at an angle ψ to the direction of motion of the straightedge; thus, from Figure A.2:

$$N = \mu_{13} W \sin(\theta + \psi) \tag{A.1}$$

$$F = \mu_{13} W \cos(\theta + \psi) \tag{A.2}$$

where μ_{13} is the coefficient of sliding friction between the slider and the surface, and W is the weight of the slider.

Now,

$$\mu_{12} = \frac{F}{N} \tag{A.3}$$

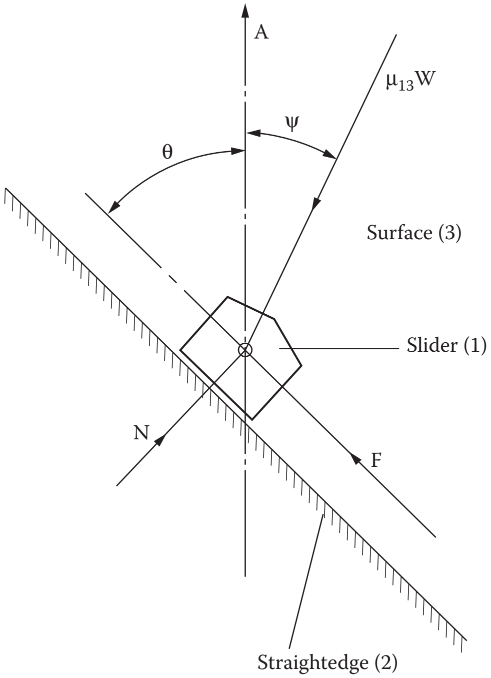


FIGURE A.2 Horizontal forces acting on a slider.

and, hence, substitution of Equation A.1 and Equation A.2 in Equation A.3 gives

$$\mu_{12} = \cot(\theta + \psi) \tag{A.4}$$

[note that $(\theta + \psi)$ is the complement of the friction angle β in Figure A.1] or

$$\tan\psi = \frac{1 - \mu_{12}\tan\theta}{\mu_{12} + \tan\theta} \tag{A.5}$$

It can now be seen that the direction in which the slider moves is independent of both its weight and the coefficient of friction between the slider and the surface.

Equation A.5 may be used to construct the required scale for a given value of θ. If θ is 45°, a convenient value for θ when $0 \le \mu_{12} \le 1.0$, Equation A.5 becomes

$$\tan\psi = \frac{1 - \mu_{12}}{1 + \mu_{12}} \tag{A.6}$$

further, if the scale is arranged parallel to the straightedge, then it is linear with respect to the coefficient of friction (Figure A.1).

A simpler way of describing the operation of this device is to argue that the slider can move only in the direction of the resultant force applied by the straightedge. This resultant force lies at an angle β (the angle of friction between the slider and the straightedge) to a line drawn normal to the straightedge and, thus, the slider moves as shown in Figure A.1. Further, because the distance read off the scale is proportional to tan β, this scale will be a linear one, giving the coefficient of friction μ_{12}.

An interesting variation of this method is illustrated in Figure A.3. Here a linear scale in μ_{12} is marked off on the straightedge. The slider is initially set at 1.0 on the scale, and the straightedge is moved a distance equal to the length of the scale multiplied by $\sqrt{2}$. The final position of the slider will give the value of the coefficient of friction.

A.3 PRECISION OF THE METHOD

Using a celluloid straightedge and a brass slider, 20 measurements of the coefficient of sliding friction were made. It was found that the mean of the readings was 0.207, with 95% confidence limits of ± 0.0043 for the mean. This result indicates the relatively high precision that can be obtained.

A.4 DISCUSSION

It is felt that the simple method for the determination of the coefficient of sliding friction between two surfaces described in this appendix has several advantages

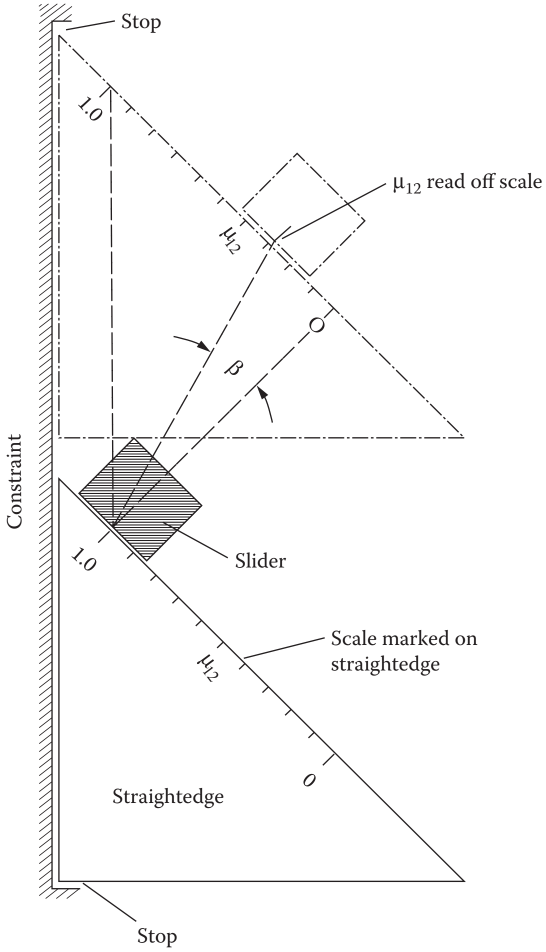


FIGURE A.3 Alternative apparatus. (From Boothroyd, G., Simple Method for the Determination of the Coefficient of Sliding Friction, *Bulletin of Mechanical Engineering Education*, Vol. 9, 1970, p. 219. With permission.)

over the methods usually employed in undergraduate laboratory demonstrations. These advantages include the following:

1. It requires the minimum of equipment.
2. No delicate adjustments of plane inclination or loading are required.
3. Relatively high precision can be obtained.
4. Repeated readings can be made quickly.
5. Readings are not affected by the static coefficient of friction.
6. Readings are not affected by the small variations in the speed of sliding.
7. It is a direct-reading method.

REFERENCE

1. Boothroyd, G., Simple Method for the Determination of the Coefficient of Sliding Friction, *Bulletin of Mechanical Engineering Education*, Vol. 9, 1970, p. 219.

Appendix B
Out-of-Phase Vibratory Conveyors

Experimental and theoretical investigations [1] have shown that certain fundamental limitations exist in the performance of conventional vibratory feeders:

1. The conveying velocity of parts up the inclined track is always less than that of parts traveling around the flat bowl base. This means that motion of parts on the track is normally obtained through the pushing action of those circulating around the bowl bottom. With this situation, there is a tendency for parts to jam in the various selecting and orienting devices fitted to the bowl track. Some parts, because of their shape, are difficult to feed under these circumstances. For example, very thin sheet parts are not able to push each other up the track. In this case, the feed rate obtained with a conventional bowl feeder is very low.

   Sometimes, it is necessary, as part of the orienting systems, to have a discontinuity in the track. Again, because the parts traveling around the bottom of the bowl cannot push those on the track beyond the discontinuity, the feed rate is generally unsatisfactory.
2. The conveying velocity of parts in a conventional vibratory-bowl feeder is very sensitive to changes in the coefficient of friction between the part and the track, and conveying velocities are very low, with low coefficients of friction.
3. For high feed rates, it is necessary for the parallel velocity of the track to be high. However, because of the method of driving a conventional vibratory-bowl feeder, an increase in the amplitude of the parallel component of vibration must be accompanied by a corresponding increase in the amplitude of the normal component of vibration. This latter increase is undesirable because, as the normal track acceleration increases above the value that causes the component to hop along the track, the mode of conveying quickly becomes erratic and unstable as a result of the bouncing of parts on impact with the track.

A new drive is described here that is suitable for all types of vibratory conveyors and solves many of the problems associated with conventional designs.

B.1 OUT-OF-PHASE CONVEYING

The new method for driving vibratory feeding devices is based on the idea that the normal and parallel components of motion of the track should have independent amplitude control and should be out of phase. Under these circumstances, the locus of a point on the track becomes elliptical instead of linear.

Theoretical and experimental work was conducted on this new type of drive, [1] and some of its advantages can be demonstrated by means of the results shown in Figure B.1. In the figure, the product of the mean conveying velocity v_m and the frequency of vibration f is plotted against the phase difference γ between the two components of motion. In the results illustrated, the ratio of the normal a_n and the parallel a_p amplitudes of vibration and the normal track acceleration were both kept constant. The relationships are plotted for three values of the coefficient of friction μ between the part and the track that cover the range likely to be met in practice. It can be seen from the figure that when the phase angle was zero, simulating a conventional feeder, the conveying velocity was very sensitive to changes in μ. Further, for values of μ less than 0.3, the part was moving backward. The results show that if the track parallel motion leads the track normal motion by 65°, the conveying velocity becomes uniformly high for all the values considered.

Figure B.2 shows the predicted effect on the mean conveying velocity v_m of changing γ in the relevant range (−90° to 0°) for three values of the amplitude ratio a_n/a_p and when the normal track acceleration A_n is kept constant. In these

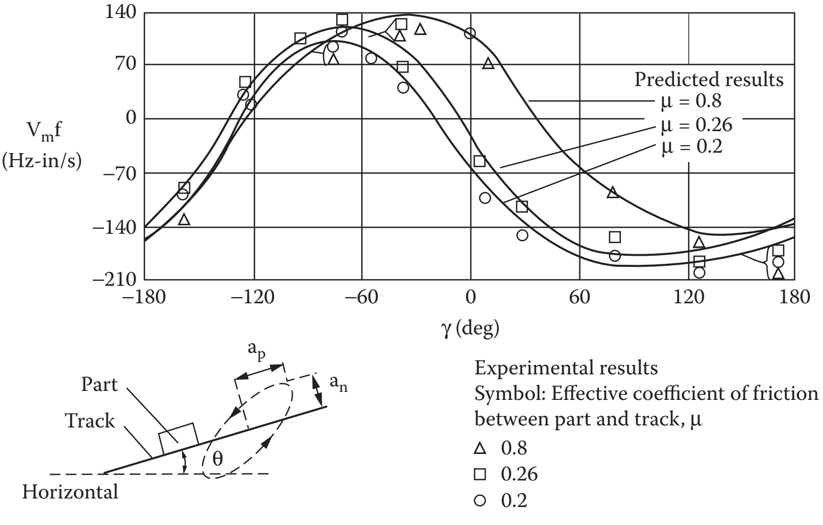


FIGURE B.1 Effect of coefficient of friction in out-of-phase conveying. γ is the phase angle, v_m the mean conveying velocity (in/sec), μ the effective coefficient of friction. Track angle θ is 4 deg; vibration frequency f, 21.5 Hz; amplitude ratio a_n/a_p, 0.365; maximum normal track acceleration a_n, 1.2 g.

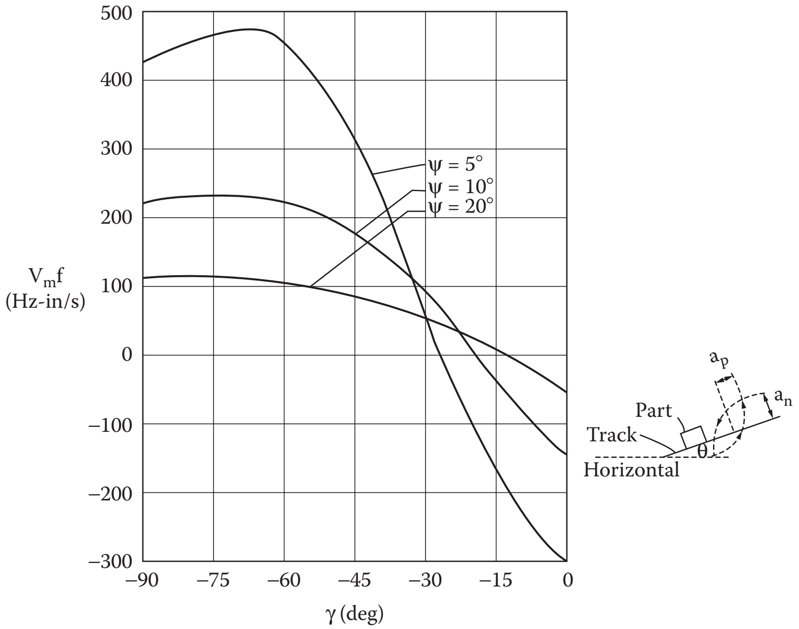


FIGURE B.2 Predicted effect of amplitude ratio ($a_n/a_p = \tan \psi$) in out-of-phase conveying; θ =4 deg, $\mu = 0.2$, $A_n = 1.2$ g.

results, a track angle of 4° and a coefficient of friction of 0.2 were chosen because these were considered to represent the most severe conditions likely to be encountered in practice. It is clear from the figure that, for conventional conveying ($\gamma = 0$), as a_p is increased, indicating an increase in the maximum parallel track velocity and a decrease in ψ, the backward conveying velocity of the parts increases. For the optimum phase angle ($\gamma = 65°$), however, the forward conveying velocity is increased as a result of an increase in a_p. It is also of interest to note that if the vibration frequency is 25 Hz, a conveying velocity as high as 18 in/sec (400 mm/sec) can be achieved.

These results show that definite advantages are to be gained from operating a vibratory-bowl feeder under the optimum out-of-phase conditions. First, the high conveying velocities attainable are almost independent of the nature of the parts being conveyed. Second, because the feed rate can be controlled by adjusting the parallel component of vibration only, the track normal acceleration may be held constant at a level that does not cause erratic movement of the parts (in the results presented, the normal track acceleration was 1.2 *g*, which represents stable conveying for most materials). Third, if a_p gradually increased as the part climbs the track, the conveying velocity of the part would gradually increase. This would result in separation of the parts as they climb the track. This situation can be

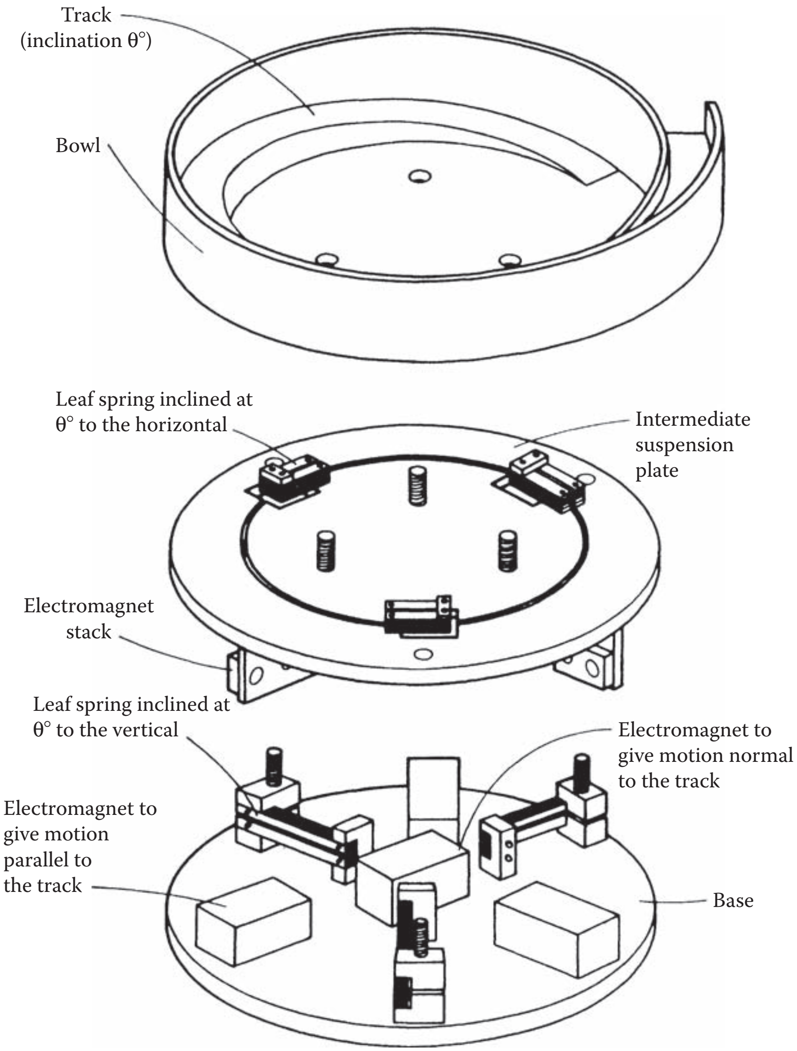


FIGURE B.3 Exploded view of a vibratory-bowl feeder drive that has independent motion normal and parallel to the bowl track.

achieved in practice by gradually increasing the track radius, and it would result in more efficient orienting and greater reliability in operation.

B.2 PRACTICAL APPLICATIONS

Figure B.3 shows an exploded view of a vibratory-bowl feeder drive unit designed to operate on the principle outlined above. In this design, motion normal to the track is imparted to the bowl through an intermediate plate supported on the base.

Motion parallel to the track is obtained through the springs that support the bowl on the plate. With a suitable controller, the two independent motions will have the required phase difference, and the situation described for out-of-phase conveying can be obtained.

As a practical example of the capabilities of the new design of feeder, an attempt was made to feed thin mica specimens that a manufacturer had previously found almost impossible to feed in a typical conventional vibratory-bowl feeder. With the new feeder, however, it was possible to feed these specimens separately up to the track at conveying velocities of up to 18 in/sec (400 mm/sec) without any erratic motion.

The new type of drive, suitable for all types of vibratory conveyors and called an out-of-phase drive, has many practical advantages. With this type of drive, feeders are quieter; greater flexibility in performance can be achieved; more reliable, yet more sophisticated, orienting devices can be employed; and much higher feed rates can be obtained than with the conventional drive system. (Note: The out-of-phase drive for vibratory conveyors has been patented by the National Research Development Corporation, and inquiries should be directed to the University of Salford Industrial Centre, Salford, Lancashire, England.)

REFERENCE

1. Redford, A.H., Vibratory Conveyors, Ph.D. thesis, Royal College of Advanced Technology, Salford, England, 1966.

Appendix C

Laboratory Experiments

This appendix gives a complete description of two typical laboratory experiments that may be included in a college or university course on automatic assembly. The first experiment is designed to illustrate certain practical aspects of the performance of a vibratory-bowl feeder; it also indicates how the results of the tests are best presented to gain the maximum information. Clearly, similar experiments could be designed to study the performance of other types of parts-feeding devices employed in automatic assembly. The second experiment illustrates how the coefficient of dynamic friction between small parts and a feed track may be obtained. This information is used in the second part of the experiment to verify the predictions of the theoretical analysis of a horizontal-delivery gravity feed track.

C.1 PERFORMANCE OF A VIBRATORY-BOWL FEEDER

C.1.1 OBJECTIVES

To determine (1) the relationship between vibration amplitude and feed rate for a constant bowl load and (2) the effect of bowl loading on the performance of a vibratory-bowl feeder.

C.1.2 EQUIPMENT

Vibratory-bowl feeder (10- or 12-in. bowl); 1000 low-carbon steel parts 5/16 in. in diameter and 1 in. long; transducer arranged to measure the vertical component of the bowl vibration amplitude; stopwatch.

C.1.3 PROCEDURE

1. For a range of settings on the bowl amplitude control and with a bowl load of 500 parts, measurements are made of the time taken for a part to travel between two marks scribed on the inside of the bowl. The vertical vibration amplitude of the bowl is also measured and, in these tests, a device is fitted to the top of the bowl track that continuously

returns the parts to the bottom of the bowl in order to maintain the bowl load constant.

2. Commencing with the bowl full (1000 parts) and the amplitude control set to give a low feed rate (less than 1 part/sec), the times are measured for successive batches of 100 parts to be delivered. In this test, the parts are allowed to pass down the delivery chute, and the readings are continued until the bowl becomes empty.

C.1.4 THEORY

Theoretical and experimental work has shown that the parameters affecting the mean conveying velocity v_m in vibratory conveying are:

1. Maximum track acceleration A (m/sec^2)
2. Operating frequency ω (rad/sec)
3. Track angle θ (see Figure C.1)
4. Vibration angle ψ (see Figure C.1)
5. Coefficient of friction between component and track μ
6. Acceleration due to gravity g (m/sec^2)

Dimensional analysis may now be applied to this problem as follows. Let

$$v_m^{a_1} = f[A^{a_2}, \omega^{a_3}, \theta^{a_4}, \psi^{a_5}, \mu^{a_6}, g^{a_7}] \tag{C.1}$$

Using the fundamental dimensions of length (L) and time (T), Equation C.1 becomes

$$\left(\frac{L}{T}\right)^{a_1} = f\left[\left(\frac{L}{T^2}\right)^{a_2}, \left(\frac{1}{T}\right)^{a_3}, \left(\frac{L}{T^2}\right)^{a_7}\right] \tag{C.2}$$

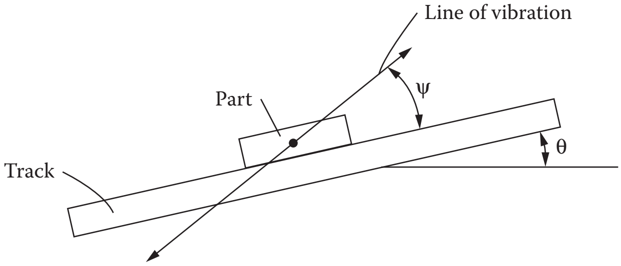


FIGURE C.1 Section of track in vibratory-bowl feeder. θ is the track angle and ψ the vibration angle.

Because the terms θ, ψ, and μ are dimensionless, they have been omitted here to simplify the work. Thus, for Equation C.1 to be dimensionally homogeneous,

$$a_1 = a_2 + a_7 \text{ and } -a_1 = -2a_2 - a_3 - 2a_7 \tag{C.3}$$

or

$$a_7 = a_1 - a_2 \text{ and } a_3 = -a_1 \tag{C.4}$$

Substituting Equation C.4 into Equation C.1 yields

$$v_m^{a_1} = f\,[A^{a_2}, \omega^{-a_1}, \theta^{a_4}, \psi^{a_5}, \mu^{a_6}, g^{a_1-a_2}]$$

or, rearranging terms with similar exponents, we obtain

$$\left(\frac{V_m\omega}{g}\right)^{a_1} = f\left[\left(\frac{A}{g}\right)^{a_2}, \theta^{a_4}, \psi^{a_5}, \mu^{a_6}\right] \tag{C.5}$$

Thus, for a given bowl and given parts, the dimensionless conveying velocity $v_m\omega/g$ is a function of the dimensionless maximum track acceleration A/g. The theoretical work described in Chapter 3 shows that it is more convenient to employ the component A_n of acceleration normal to the track. It was also shown, however, that conveying is generally achieved by the pushing action of the parts circulating around the flat bowl base. In this case, the effective track angle is zero and, therefore, A, in the analysis above, should be taken as the vertical component A_v of the bowl acceleration.

If it is assumed that the bowl moves with simple harmonic motion, the maximum bowl acceleration may be obtained from measurements of the vertical bowl amplitude and a knowledge of the operating frequency ω.

In the second part of the experiment, the mean feed rate F_0 for each increment in bowl load will be given by

$$F_0 = \frac{100}{t_f}\,\text{parts/sec} \tag{C.6}$$

where t_f is the time taken (in seconds) to feed 100 parts.

C.1.5 PRESENTATION OF RESULTS

Figure C.2 and Figure C.3 show results obtained with a typical commercial bowl feeder. In Figure C.2, the dimensionless mean conveying velocity $v_m\omega/g$ is plotted against the dimensionless vertical bowl acceleration A_v/g. It can be seen that feeding occurs for all values of A_v/g greater than 0.32 and, from this, it is possible to estimate the coefficient of static friction μ_s between the parts and the track using the analysis described in Chapter 3. Thus,

$$\mu_s = \frac{\cot\psi}{g/A_0 - 1} \tag{C.7}$$

where ψ is the vibration angle, A_0 the minimum vertical acceleration of the bowl for feeding to occur, and g the acceleration due to gravity. In the results presented here, μ_s was estimated to be 0.95 for a mild-steel part in a rubber-coated bowl.

Figure C.3 shows the changes in feed rate F_0 as the bowl gradually empties. It can be seen that, as the bowl load was reduced, the feed rate increased rapidly. Clearly, when the bowl is empty, the feed rate will have fallen to zero. For the amplitude setting employed in this test, the bowl could be used to feed the cylindrical parts to a machine or workhead requiring about 40 parts/min. It is

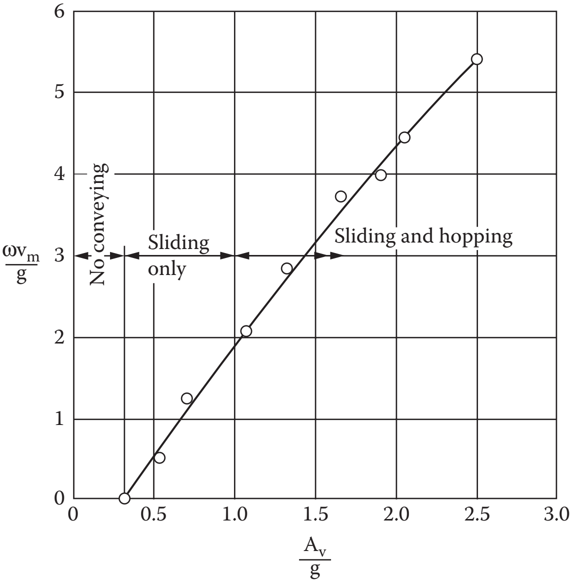


FIGURE C.2 Effect of vertical bowl acceleration on conveying velocity for a commercial vibratory-bowl feeder. Mild-steel cylindrical parts $^5/_{16}$ in. in diameter × 1 in. long; bowl load 500; spring angle 65°; vibration frequency 50 Hz.

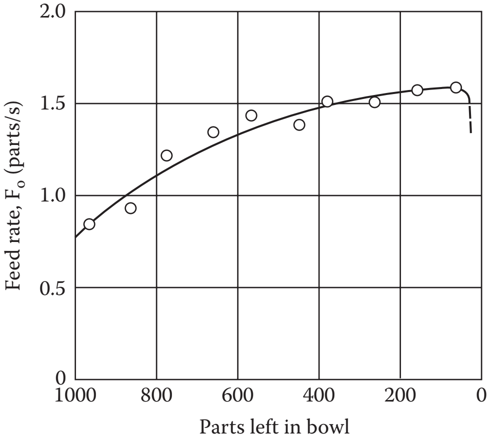


FIGURE C.3 Load sensitivity of commercial vibratory-bowl feeder. Mild-steel cylindrical parts 5/16 in. in diameter × 1 in. long; rubber-coated track; spring angle 65°; vibration frequency 50 Hz.

clear that, because of the large increase in feed rate as the bowl empties, excessive recirculation of the parts would occur.

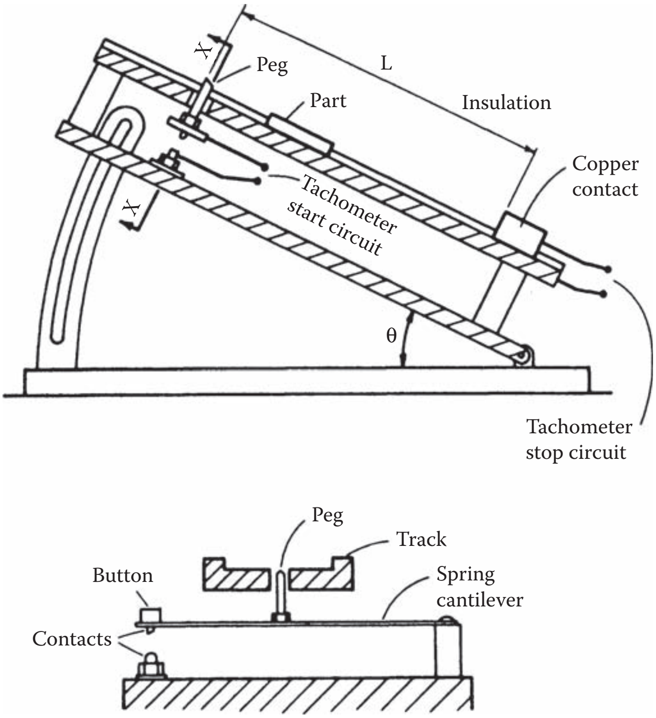
C.2 PERFORMANCE OF A HORIZONTAL-DELIVERY GRAVITY FEED TRACK

C.2.1 Objectives

1. To determine the coefficient of dynamic friction μ_d between the parts and feed track used in the experiment
2. To examine experimentally and theoretically the performance of a horizontal-delivery gravity feed track

C.2.2 Equipment (Objective 1)

The equipment used in the determination of the coefficient of dynamic friction consisted (Figure C.4) of a straight track whose angle of inclination θ to the horizontal could be varied between 20° and 60°. The equipment is designed to record accurately the time taken for a part to slide from rest a given distance down the track. Near the top of the track, a short peg projecting upward through a hole in the track retains the part until the spring cantilever supporting the peg is deflected by depressing the button. The deflection of the cantilever also closes a pair of contacts at the moment the part is released; this initiates the count on a digital clock. A further contact is positioned at the bottom of the track a distance



Enlarged section X-X

FIGURE C.4 Apparatus used in the determination of the coefficient of dynamic friction.

L from the front of the retaining peg. When the part arrives at the bottom of the track, it completes the circuit, which stops the count on the clock.

C.2.3 THEORY (OBJECTIVE 1)

The equation of motion for a part sliding down an inclined track is

$$m_p a = m_p g \sin\theta - \mu_d m_p g \cos\theta$$

or

$$\frac{a}{g} = \sin\theta - \mu_d \cos\theta \tag{C.8}$$

when m_p is the mass of the part, θ the track inclination, *a* the acceleration of the part, and μ_d the coefficient of dynamic friction between the part and the track.

For a straight inclined track, the acceleration of the part is uniform, and the time t_s taken for the part to slide a distance *L* is given by

$$t_s^2 = \frac{2L}{a} \tag{C.9}$$

Combining Equation C.8 and Equation C.9 gives

$$\mu_d = \frac{\sin\theta - 2L/gt_s^2}{\cos\theta} \tag{C.10}$$

C.2.4 PROCEDURE (OBJECTIVE 1)

In the present experiment, where the part was of mild steel and the track of aluminum alloy, the times were measured for the part to slide a distance of 4 in. (101.6 mm), with the track angle set at 30°, 45°, and 60°. For each condition, 20 readings were taken and averaged, and the 95% confidence limits for each average were computed using the *t* statistics. The corresponding values of μ_d were computed using Equation C.10.

C.2.5 RESULTS (OBJECTIVE 1)

The mean values of μ_d obtained from each track angle are presented in Table C.1, together with their corresponding 95% confidence limits. Because no significant variation of μ_d with changes in track angle was evident, it was thought reasonable to take the average of all the readings obtained. This yielded a mean value of μ_d of 0.353 with a range, for 95% confidence, of 0.325–0.381.

TABLE C.1
Mean Values of μ_d and 95% Confidence Limits

θ, Degree	μ_d	95% Confidence Limits
30	0.358	± 0.028
45	0.354	± 0.012
60	0.347	± 0.006

C.2.6 EQUIPMENT (OBJECTIVE 2)

Figure C.5 shows the design of the experimental horizontal-delivery feed track. A parts-release and timing arrangement similar to that used in the first part of the experiment is provided. In this case, the column of parts is retained by a peg positioned on the horizontal section 2 in. (50.8 mm) from the beginning of the

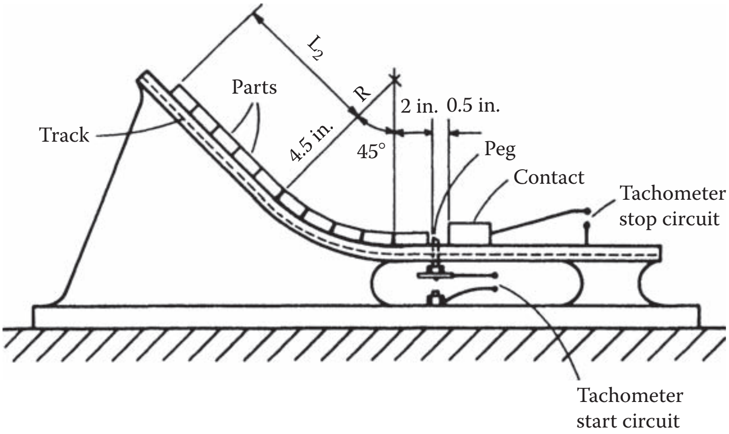


FIGURE C.5 Apparatus used to investigate the performance of a gravity feed track.

curved section, and the contact that arrests the column of parts and stops the count is positioned 0.5 in. (12.7 mm) from the front of the peg.

C.2.7 THEORY (OBJECTIVE 2)

The derivation of the theoretical expression for the initial acceleration on release of a column of parts held in a feed track of the present design was developed in Chapter 5. See Equation 5.10.

Substitution of the values of $L_1 = 2$ in. (50.8 mm), $R = 4.5$ in. (114.3 mm), and $\alpha = 45°$ for the experimental rig and the mean, upper, and lower values of $\mu_d = 0.353$, 0.325, and 0.381, respectively, obtained in the first part of the experiment gives the required predicted relationship between a/g and L_2.

In the experiment, the time t_p (sec) was recorded for the column of parts to slide a distance of 0.5 in. (12.7 mm). Because this distance was small compared to the dimensions of the feed track, it could be assumed that the acceleration a of the column of parts was constant. Thus,

$$\frac{a}{g} = \frac{2(0.5)}{gt_p^2} = \frac{2.59 \times 10^{-3}}{t_p^2} \tag{C.11}$$

C.2.8 PROCEDURE (OBJECTIVE 2)

The time was recorded for the parts to slide 0.5 in. (12.7 mm) for a range of values of L_2. For each condition, an average of 20 readings was obtained.

C.2.9 RESULTS (OBJECTIVE 2)

The experimental results are plotted in Figure C.6, together with the two curves representing the 95% confidence limits. It can be seen that all the experimental results fall within the two theoretical curves representing the 95% confidence limits for the mean value of μ_d.

C.2.10 CONCLUSIONS

1. The coefficient of friction between the parts and the track used in the experiment has been successfully determined.
2. The experimental results obtained for the acceleration of a column of parts in a horizontal-delivery gravity feed track fall within the range, for 95% confidence, of predicted values using the result of the analysis and the values of μ_d obtained in the first part of the experiment. This confirms that the theory, determined for parts of an infinitesimally small length, is valid for parts of finite length, provided that this length is small compared to the dimensions of the track.
3. The performance of parts in a horizontal-delivery gravity feed track can be accurately estimated using the theoretical equation, provided that the coefficient of dynamic friction between the parts and the track is known.

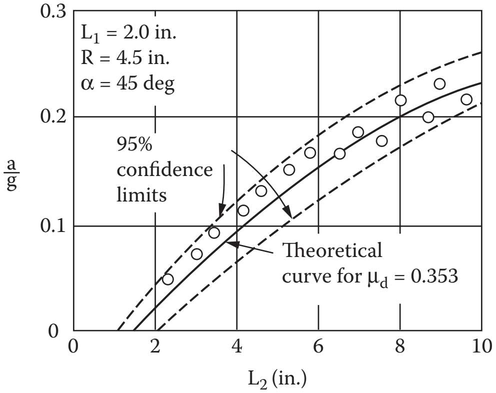


FIGURE C.6 Performance of a horizontal-delivery gravity feed track (steel parts on aluminum track).

Appendix D

Feeding and Orienting Techniques for Small Parts

This appendix contains a coding system for small parts and a series of solutions to typical small-part feeding and orienting problems for automatic assembly. The purpose of the coding system in Section D.1 is to allow parts to be divided into groups having similar feeding and orienting problems. If an engineer is interested in designing a feeding and orienting system for a particular part then the first step is to code the part. Section D.2 gives examples of feeding and orienting systems catalogued under part code numbers. Even though the example for a particular code may be for a different part other than the one under consideration, it should present similar feeding and orienting problems and be capable of automatic handling by similar means.

Section D.3 presents a classification of individual orienting devices for vibratory-bowl feeders and data sheets showing their behavior.

Finally, Section D.4 contains data sheets with details of common nonvibratory (mechanical) feeders.

This appendix is based on the *Handbook of Feeding and Orienting Techniques for Small Parts* published at the University of Massachusetts, Amherst, under the authorship of G. Boothroyd, C.R. Poli, and L.E. Murch. The handbook was based on research work carried out at the university and supported by the National Science Foundation, together with contributions from industry.

D.1 CODING SYSTEM

This section contains the following:

1. Introduction to the coding system
2. Coding examples
3. Sample parts for practice
4. Analysis of the coding of the sample parts
5. Coding system for small parts

It is suggested that, after reading the instructions, the reader attempts to code the sample parts. The code numbers obtained should then be finally checked against the solutions.

D.1.1 INTRODUCTION TO THE CODING SYSTEM

The three-digit coding system is designed for small parts that are to be automatically fed and oriented. To determine the code, the basic shape, important features, and various symmetries of a part are considered.

The feeding and orienting characteristics of a part will generally be based on its geometry. In this case, the part will be assigned a first digit of 0-8 depending on its basic shape. Under some circumstances, other features (such as fragility, size, etc.) override geometric considerations and can make a part difficult to feed. These parts are assigned a first digit of 9 and can be described by one or more of the following: flexible, delicate, sticky, light, overlap, large, very small, nest or severely nest, tangle or severely tangle, and abrasive.

For parts with a first digit of 9, there is a separate choice for the second and third digits of the 3-digit code defining the appropriate difficulty characteristics of the part. When a part is defined as difficult-to-feed, this does not necessarily mean that feeding and orienting at acceptable rates is impossible but that a specialized feeding device is likely to be required.

In the following some of the terminology is introduced.

Envelope

The envelope of a part is the smallest cylinder, regular prism or rectangular prism that can enclose the part when small projections are neglected (Figure D.1). When the choice of envelope is not clear, the one that has the maximum contact with the part should be chosen.

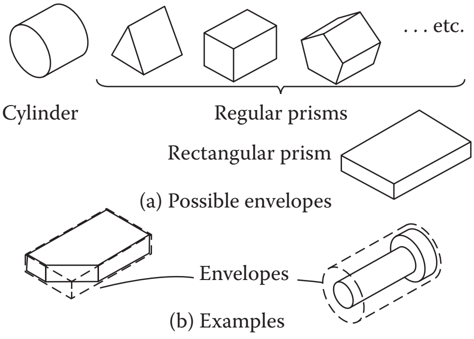


FIGURE D.1 Part envelope.

To determine the first digit of the coding system (except for the first digit of 9) it is necessary to know the basic shape of the part and the dimensions of its envelope.

For a part with a rectangular envelope, A is the length of the longest side of the envelope, C is the length of the shortest side and B is the length of the intermediate side (Figure D.2). For all other parts, L is the length of the cylindrical envelope of the part and D is the diameter of the cylindrical envelope (Figure D.3).

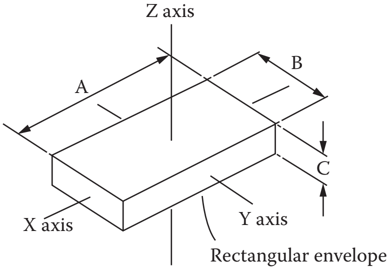


FIGURE D.2 Dimensions of rectangular part.

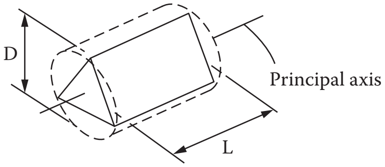


FIGURE D.3 Dimensions of rotational, triangular, or square parts.

Features

Geometric features include steps, chamfers, holes, grooves, and projections. Other features, such as paint, lettering, or geometric features that cannot be described macroscopically (such as surface finish, etc.) are called nongeometric features. Except for features that do not require orientation such as the slot in the head of a screw, all other features that can be used to define the orientation of a part are candidate features for coding. However, only the set of features that can be utilized most efficiently is coded. The importance of a feature is evaluated by the probability that the feature will interact with an orienting device. The less the probability, the less the importance of the feature will be. Therefore, the geometric shape, the location, and the size of a feature are major factors to be considered during the coding process. Some examples are shown in Figure D.4.

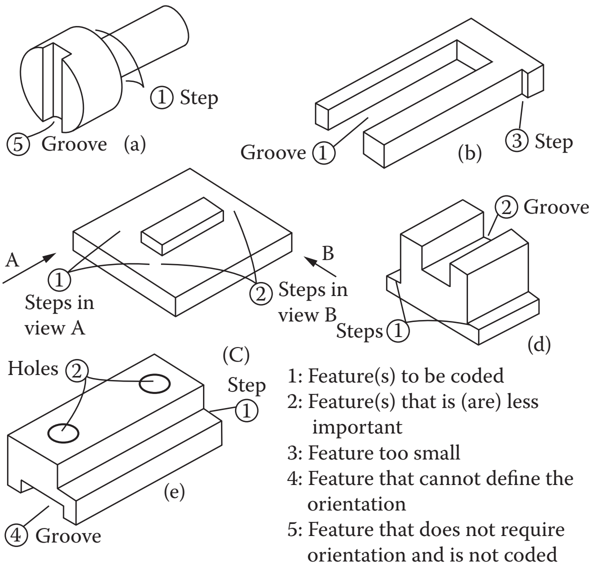
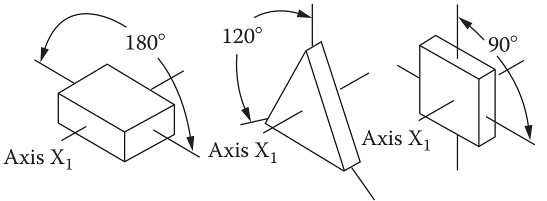

① Step
⑤ Groove
(a)
Groove ①
(b)
③ Step
A
① Steps in view A
B
② Steps in view B
② Groove
Steps ①
(d)
Holes ②
(C)
Step ①
(e)
④ Groove
1: Feature(s) to be coded
2: Feature(s) that is (are) less important
3: Feature too small
4: Feature that cannot define the orientation
5: Feature that does not require orientation and is not coded

FIGURE D.4 Relative importance of features.

Rotational Symmetry

Rotational symmetry means that the orientation of a part is repeated when the part is rotated through a specific angle, about a selected axis. There are special cases like solids of revolution having zero rotational symmetry about their axis because their orientation is preserved after a rotation through any angle about the axis. Figure D.5 shows several examples.



(a) 180° rotational symmetry about axis X_1 (b) 120° rotational symmetry about axis X_1 (c) 90° rotational symmetry about axis X_1

FIGURE D.5 Examples of rotational symmetries.

In general, a part may have rotational symmetry about several axes. However, these symmetries are not mutually independent. For instance, if a part has 180° rotational symmetry about two of its three mutually perpendicular axes (Figure D.6), then it must have 180° rotational symmetry about the third axis. If a group of features has a certain rotational symmetry, then it can be considered as one feature (Figure D.7). At most two features are needed to completely define the orientation of a part.

The features that do not require orientation should be ignored during the coding of a part. Figure D.4a shows an example. The slot in the head of the screw should be disregarded when this part is coded.

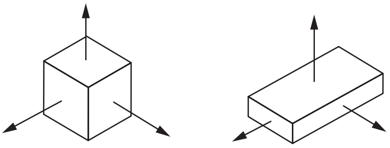
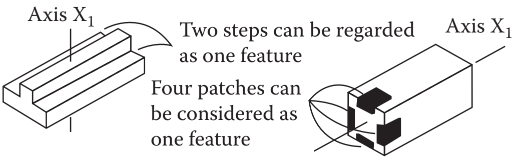

(a) (b)

FIGURE D.6 Axes of symmetry.


Axis X_1
Two steps can be regarded as one feature
Axis X_1
Four patches can be considered as one feature

(a) Features having 180° rotational symmetry about axis X_1

(b) Features having 90° rotational symmetry about axis X_1

FIGURE D.7 Groups of features having rotational symmetry.

For parts having a cylindrical or regular prismatic shape, the axis that is perpendicular to the circular or regular polygonal cross section of the envelope is called the principal axis (e.g., the X_1 axis in Figure D.5b and Figure D.5c). The axes perpendicular to the principal axis are called transverse axes (e.g., all axes shown in Figure D.5b and Figure D.5c except the X_1 axis). If a part has 180° rotational symmetry about at least one of its transverse axes, then it does not require orientation end to end and is ALPHA symmetric. If a part does not require orientation about its principal axis, then it is BETA symmetric (Figure D.8).

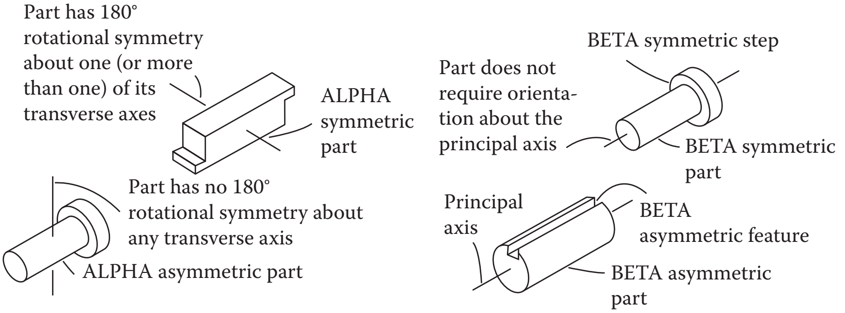

Part has 180° rotational symmetry about one (or more than one) of its transverse axes
ALPHA symmetric part
Part has no 180° rotational symmetry about any transverse axis
ALPHA asymmetric part
BETA symmetric step
Part does not require orientation about the principal axis
BETA symmetric part
Principal axis
BETA asymmetric feature
BETA asymmetric part

FIGURE D.8 Examples of ALPHA and BETA symmetries.

Surfaces and Views of Rotational, Triangular, or Square Parts

The side surface is the surface of the envelope parallel to the principal axis and the end surface is the surface of the envelope perpendicular to the principal axis (Figure D.9).

The side view is the view in a direction perpendicular to the principal axis and parallel to the plane on which the part rests and the end view is the view in a direction parallel to the principal axis (Figure D.9).

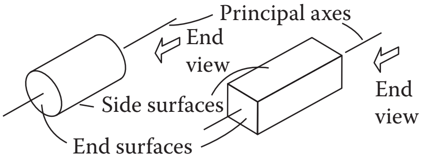


FIGURE D.9 Part views and surfaces.

D.1.2 CODING EXAMPLES

Example 1

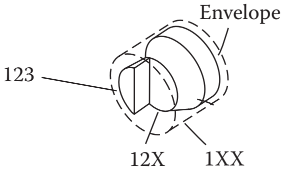


FIGURE D.10 Rotational part.

Digit 1: The part shown in Figure D.10 has a cylindrical envelope and thus the first digit is 0, 1 or 2. The L/D ratio of the envelope is between 0.8 and 1.5. Thus, the first digit is 1.

Digit 2: The table for the second and third digits for rotational parts is now used. The instructions and notes for the second digit are read starting with 0 until an appropriate digit is found. Because the part has a BETA-symmetric chamfer on its external surface and it does not satisfy the descriptions for a second digit of 0 or 1, the second digit is 2.

Digit 3: The instructions and notes for the third digit are read staring with 0 until an appropriate digit is found. In the present example, because the projection on the end surface is the main feature that causes BETA-asymmetry, the third digit is 3. The code for the part is 123.

Example 2

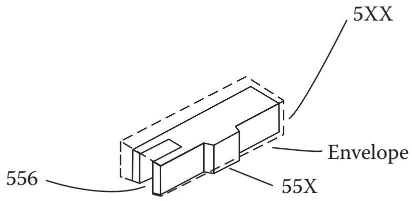


FIGURE D.11 Square part.

Digit 1: The part shown in Figure D.11 has a square prismatic envelope and thus the first digit is 3,4, or 5. The L/D ratio of the smallest cylinder that can completely enclose the part is greater than 1.5. Thus, the first digit is 5.

Digit 2: Because this part has no rotational symmetry about the principal axis, due to the steps external to the envelope, the second digit is 5.

Digit 3: Because the through groove on the end surface is the feature that causes ALPHA asymmetry, the third digit is 6. The code for the part is 556.

Example 3

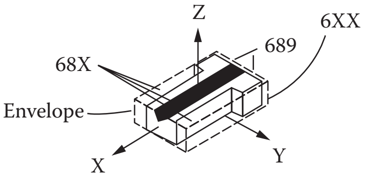


FIGURE D.12 Rectangular part.

Digit 1: The part shown in Figure D.12 has a rectangular prismatic envelope and thus the first digit is 6, 7, or 8. Because the ratio A/B is less than 3 and the ratio A/C is greater than 4, the first digit is 6.

Digit 2: Two features are needed to completely define the orientation of this part. One of them is rotationally symmetric about the Z axis and the other (pair) is rotationally symmetric about the X axis. Thus, the second digit is 8.

Digit 3: The nongeometric feature that is rotationally symmetric about the Z axis will give the largest third digit, 9. The code for the part is 689.

Example 4

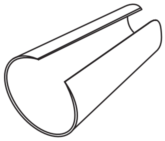
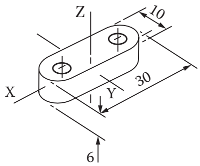


FIGURE D.13 Difficult to feed part.

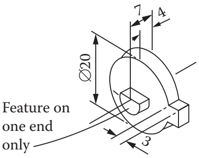
Because the part shown in Figure D.13 will nest severely, the code is 9XX. The last two digits are chosen by the special code for parts that are difficult to feed. The code for the part is 908.

D.1.3 Sample Parts for Practice

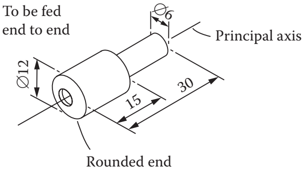
The solid metal parts shown on this page are to be coded by the reader. The solutions are given in the following pages.



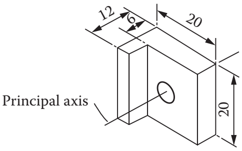
1 Code No. _ _ _



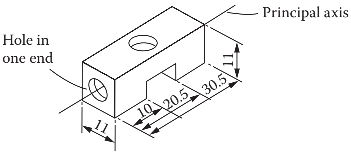
2 Code No. _ _ _



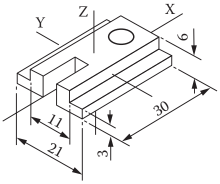
3 Code No. _ _ _



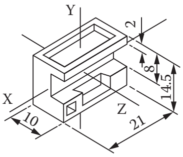
4 Code No. _ _ _



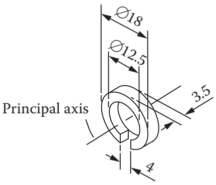
5 Code No. _ _ _



6 Code No. _ _ _



7 Code No. _ _ _



8 Code No. _ _ _

Note: All dimensions in mm.

D.1.4 ANALYSIS OF THE CODING OF THE SAMPLE PARTS

Example 1: Code No. 600

Digit 1: The envelope of this part is a rectangular prism. Thus, the first digit is 6,7 or 8. For the envelope,

A/B = 30/10 = 3

A/C = 30/6 = 5.

Thus, the first digit is 6.

Digit 2: This part has 180° rotational symmetry about all three axes. Therefore, the second digit is 0.

Digit 3: Because three adjacent surfaces of the envelope have significant differences in dimensions, the third digit is 0. The remaining features are not needed for orienting purposes.

Example 2: Code No. 074

Digit 1: The envelope is the cylinder that encloses the part without the two projections, giving a first digit of 0, 1, or 2. For the envelope,

L/D = 7/23 = 0.3

Thus, the first digit is 0.

Digit 2: This part has a feature on one end only, therefore it is not ALPHA symmetric. Furthermore, the feature causing ALPHA asymmetry is not BETA symmetric, thus the second digit is 7.

Digit 3: This part has BETA-asymmetric projections on both side and end surfaces so that the third digit is 4.

Example 3: Code No. 220

Digit 1: The envelope of this part is the cylinder that completely encloses the part, and the first digit is 0, 1, or 2. For the envelope,

L/D = 30/12 = 2.5

Thus, the first digit is 2.

Digit 2: This part has a BETA-symmetric step. However, it cannot be fed in a slot because its center of mass is not within the shank. Thus, the second digit is 2. The concentric blind hole on the rounded end surface is not required for orienting.

Digit 3: The part will be fed end to end and, therefore, the third digit is 0.

Example 4: Code No. 354

Digit 1: The envelope is the square prism that encloses the part without the rib. Thus the first digit is 3, 4, or 5. The L/D ratio of the circumscribed cylinder is

$$L/D = 12/20\sqrt{2} = 0.42$$

Digit 2: The part has no 180° rotational symmetry about the principal axis, and there is a step in the side view. Therefore, the second digit is 5. The hole at the center of the end surface is not the feature that causes rotational asymmetry and is therefore not a main feature.

Digit 3: Due to the rib on the end surface, this part is not 180° rotationally symmetric about any of its transverse axes. As this rib provides a step on the end surface, the third digit is 4.

Example 5: Code No. 578

Digit 1: The envelope of this part is a square prism and the first digit is 3, 4, or 5. From the circumscribed cylinder of the envelope,

$$L/D = 30.5/11\sqrt{2} = 1.93$$

Thus, the first digit is 5.

Digit 2: The through groove on the side surface causes rotational asymmetry about the principal axis. The blind hole on the side surface also causes rotational asymmetry but is secondary to the groove. Thus, the second digit is 7.

Digit 3: The blind hole on the end surface is the only feature that results in rotational asymmetry about all transverse axes. Hence, the third digit is 8.

Example 6: Code No. 685

Digit 1: This part has a rectangular prismatic envelope and the first digit is 6, 7, or 8. For the envelope,

$$A/B = 30/21 = 1.5$$

$$A/C = 30/6 = 5$$

Thus, the first digit is 6.

Digit 2: This part has no rotational symmetry, and no single feature can define the orientation of the part. The orientation of this part is defined by the steps symmetric about the Z axis and by the through groove that is symmetric about the X axis. Thus, the second digit is 8.

Digit 3: The steps parallel to the X axis would give a third digit of 0. The through groove parallel to the Z axis gives a third digit of 5. The third digit is, therefore, 5, as it is the largest of the two possible digits.

Example 7: Code No. 853

Digit 1: This part has a rectangular prismatic envelope and thus the first digit is 6, 7, or 8. For the envelope,

$A/B = 21/10 = 2.1$

$A/C = 21/14.5 = 1.5$

Thus, the first digit is 8.

Digit 2: The part has no rotational symmetry, its orientation can be defined by one feature, the through groove, and it has no symmetric plane so that the second digit is 5.

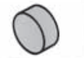
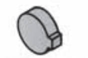
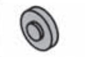
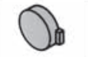
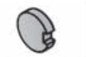
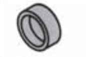
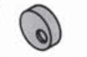
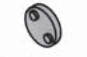
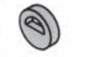
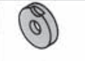
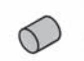
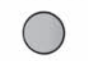
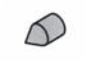
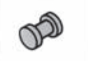
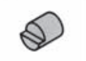
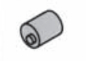
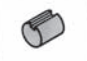
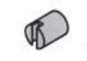
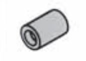
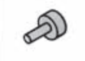
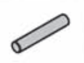
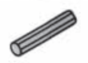
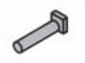
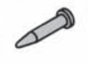
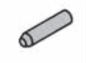
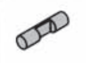
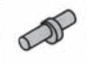
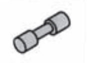
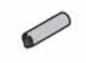
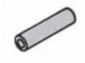
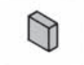
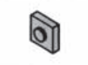
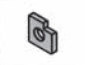
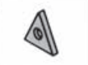
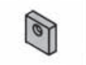
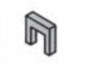
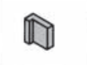
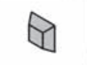
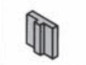
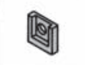
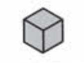
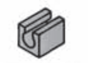
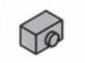
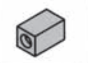
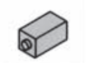
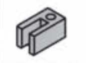
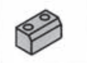
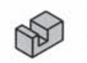
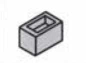
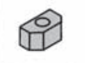
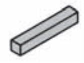
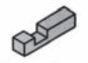
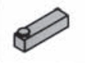
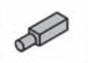
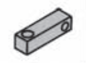
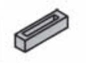
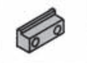
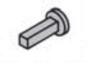
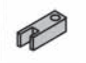
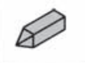
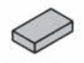
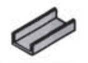
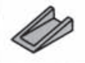
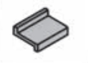
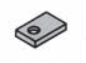
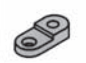
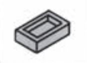
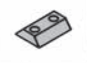
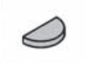
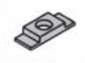
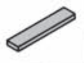
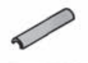
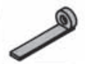
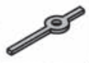
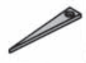
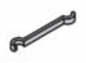
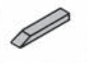
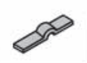
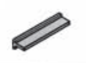
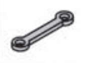
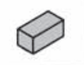
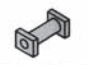
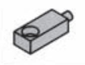
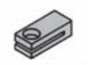
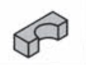
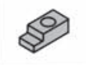
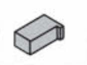
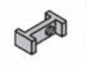
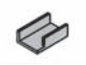
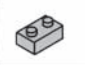
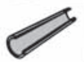
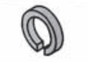
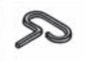
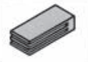
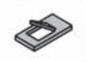
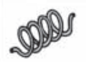
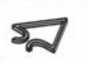
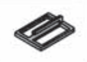
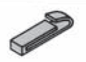
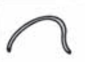
Digit 3: The through groove is parallel to the X axis and, thus, the third digit is 3. All other features will give larger third digit codes; thus, they are ignored.

Example 8: Code No. 904

This part is difficult to feed because it will tangle and thus the first digit is 9. Because tangling is the only feature making the part difficult to feed, the code is 904.

D.1.5 CODING SYSTEM FOR SMALL PARTS

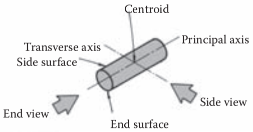
Small Parts for Automatic Handling (Choice of the first digit)

Parts can easily be fed (but not necessarily oriented) using conventional hopper feeders (see note 1)	Rotational parts (see note 2)	L/D < 0.8 (see note 5)	Discs	**0**										
		0.8 ≤ L/D ≤ 1.5 (see note 5)	Short cylinders	**1**										
		L/D > 1.5 (see note 5)	Long cylinders	**2**										
	Triangular or square prismatic parts (see note 3)	L/D < 0.8 (see note 5)	Flat parts	**3**										
		0.8 ≤ L/D ≤ 1.5 (see note 5)	Cubic parts	**4**										
		L/D > 1.5 (see note 5)	Long parts	**5**										
	Rectangular parts (see note 4)	A/B ≤ 3, A/C > 4 (see note 6)	Flat parts	**6**										
		A/B > 3 (see note 6)	Long parts	**7**										
		A/B ≤ 3, A/C ≤ 4 (see note 6)	Cubic parts	**8**										
Parts are difficult to feed using conventional hopper feeders (see note 1)				**9**										

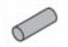
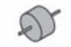
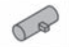
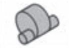
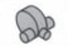
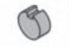
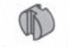
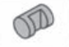
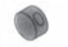
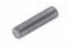
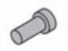
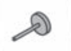
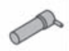
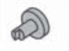
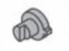
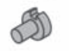
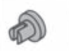
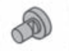
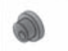
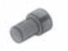
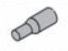
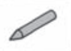
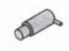
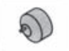
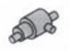
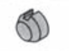
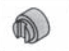
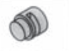
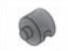
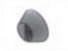
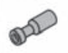
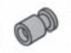
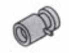
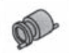
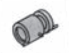
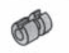
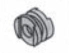
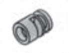
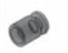
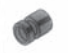
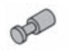
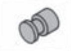
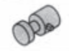
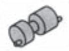
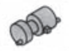
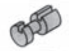
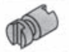
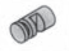
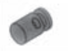
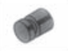
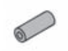
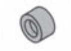
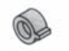
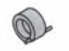
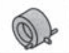
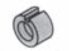
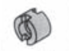
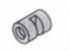
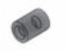
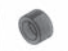
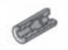
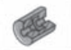
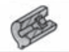
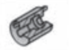
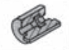
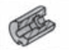
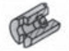
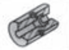
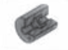
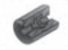
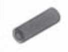
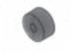
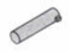
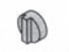
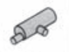
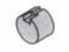
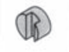
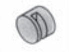
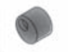
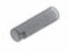
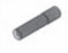
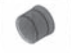
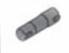
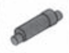
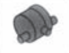
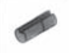
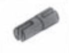
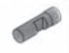
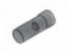
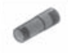
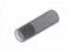
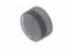
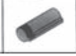
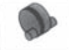
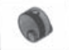
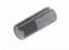
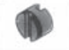
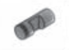
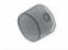
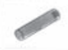
Small Parts for Automatic Handling (Choice of the first digit)

1. A first digit of 0-8 is for parts that can be fed easily (but not necessarily oriented) using conventional vibratory or nonvibratory hopper feeders. Parts having characteristics making them difficult to feed, irrespective of basic shape, are assigned a first digit of 9. Difficult-to-feed parts include those that are flexible, delicate, sticky, light, overlap, large, very small, nest, severly nest, tanlge, severly tangle or are abrasive.
2. A part whose basic shape is a cylinder or regular prism whose cross section is a regular polygon of five or more sides is called a rotational part.
3. A part whose basic shape is a regular prism whose cross section is a regular polygon of three or four sides is called a triangular or square part.
4. A part whose basic shape is a regular prism is called a rectangular part.
5. L is the length and D is the diameter of the smallest cylinder that can completely enclose the part.
6. A is the length of the longest side, C is the length of the shortest side, and B is the length of the intermediate side of the smallest rectangular prism that can completely enclose the part.

Rotational Parts (Parts with a first digit of 0, 1, or 2)



THIRD DIGIT

				Part is BETA symmetric (see note 9)		Part is not BETA symmetric [code the main feature or features causing BETA asymmetry] (see note 10)							
				To be fed end-to-end (see note 11)	To be fed side-by-side (see note 11)	BETA asymmetric projections [can be seen in silhouette]			BETA asymmetric grooves, holes, recessess on external surfaces				Other features, slight asymmetry, features too small or, non-geometric features [such as paint, lettering, etc.]
						On side surface only	On end surfaces only	On both side and end surfaces	Through grooves can be seen in end view	Through grooves cab be seen in a side view		Holes or recesses [cannot be seen in outer shape of silhouette in end views]	
										On end surfaces	On side surface		
SECOND DIGIT				**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Part is ALPHA symmetric (see note 2)			**0**										
Part is not ALPHA symmetric [code the main feature or features, causing ALPHA asymmetry] (see note 3)	Part can be fed in a slot supported by large end or protruding flange with center of mass below supporting surfaces (see note 4)		**1**										
	BETA symmetric steps or chamfers on external surfaces (see note 5)		**2**										
	BETA symmetric grooves, holes or recesses (see note 6)	On both side and end surfaces	**3**										
		On side surface only	**4**										
		On end surfaces only	**5**										
	BETA symmetric hidden features with no corresponding exposed features (see note 7)		**6**										
	BETA asymmetric features or BETA symmetric parts with features other than steps, chamfers or tapers but too small for orientation purposes (see note 9)		**7**										
	BETA symmetric step, chamfer or taper too small for orientation purposes		**8**										
	Other features, slight asymmetry, features too small or non-geometric features [such as paint, lettering, etc.] (see note 8)		**9**										

Rotational Parts (Parts with a first digit of 0, 1, or 2)

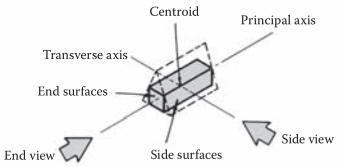
1. A rotational part is one whose basic shape is a cylinder or regular prism having five or more sides. The part is not difficult to feed.
2. The part does not require orientation end to end.
3. A main feature causing ALPHA asymmetry is one defining the end-to-end orientation of the part.
4. These are parts that will orient themselves with their principal axis vertical when placed in a parallel-sided horizontal slot.
5. A BETA-symmetric step or chamfer is a concentric reduction in diameter. The cross section can be circular or any regular polygon of four or more sides. Discrete projections, recesses or irrelevant features should be ignored in choosing this digit.
6. The reductions and increases in diameter forming the groove must be concentric. The cross sections can be circular or any regular polygon of four or more sides. Discrete projections, recesses or irrelevant features should be ignored in choosing this digit.
7. These parts have an ALPHA-symmetric external shape but their center of mass is not at the geometric center of the part.
8. If exposed features are prominent but the symmetry caused by these features is too small to be employed for orienting purposes, then the symmetry is said to be slight asymmetry.
9. A BETA-symmetric part does not require orientation about its principal axis.
10. A main feature causing BETA asymmetry is one that completely defines the orientation of the part about its principal axis.
11. Some parts can only be fed one way. However, when a choice exists, the technique employed and hence the code can be affected by the delivery orientation.

Triangular and Square Parts (Parts with a first digit of 3, 4, or 5)

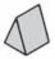
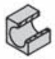
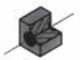
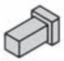
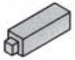
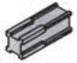
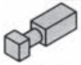
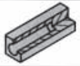
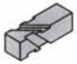
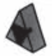
1. A part whose basic shape is a regular prism whose cross section is an equilateral triangle or square is called a triangular or square part. The part is not difficult to feed.
2. Part does not require orientation about its principal axis.
3. A part has rotational symmetry about a specified axis if the part's orientation is repeated by rotating it through a certain angle (less than 360 deg) about that axis.
4. When the envelope of a part is a perfect cube, the principal axis should be selected according to the following priorities:
   a. Any axis about which the part is 90 deg rotationally symmetric.
   b. An axis about which the part has 180 deg rotational symmetry and clearly not 90 deg rotational symmetry.
   c. An axis about which the part has 180 deg rotational symmetry and almost 90 deg rotational symmetry.
   d. When a part has no rotational symmetry and there is more than one main feature, the principal axis should be the axis of symmetry of one of the main features.

   When utilizing the above rules and multiple choices still exist, then the axis that will provide a code with the smallest third digit should be selected as the principle axis.
5. Part does not require orientation end to end (it has 180 deg rotational symmetry about at least one transverse axis).
6. A main feature causing ALPHA asymmetry defines the end-to-end orientation of the part and distinguishes the end and side surfaces.
7. The various aspects of a part resting on a plane are called natural resting aspects.
8. If exposed features are prominent but the symmetry caused by these features is too small to be employed for orienting purposes, then the asymmetry is said to be slight asymmetry. When the part is 180 rotationally symmetric about a certain axis, slight asymmetry implies that the part is almost 90 deg rotationally symmetric about the same axis.
9. Steps, chamfers or through grooves are features which result in a deviation of the silhouette of the part from the silhouette of its envelope.
10. These are parts that will orient themselves with their principal axis vertical when placed in a parallel-sided horizontal slot.

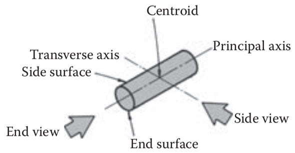
Triangular and Square Parts (Parts with a first digit of 3, 4, or 5)

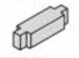
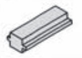
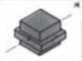
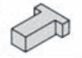
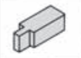
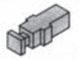
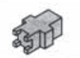
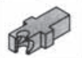
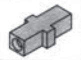
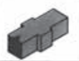
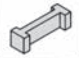
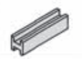
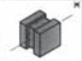
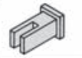
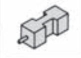
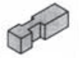
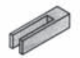
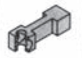
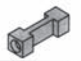
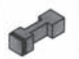
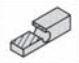
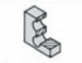
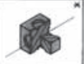
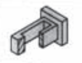
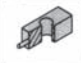
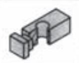
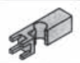
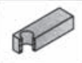
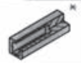
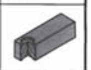
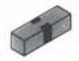
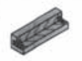
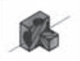
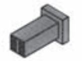
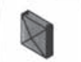
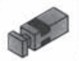
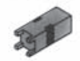
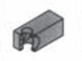
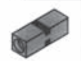
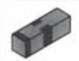
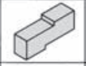
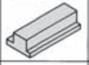
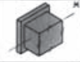
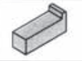
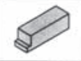
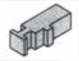
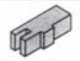
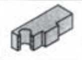
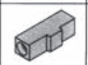
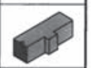
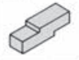
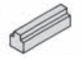
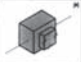
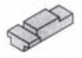
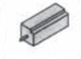
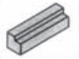
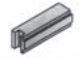
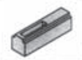
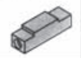
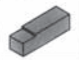
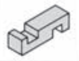
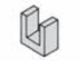
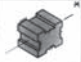
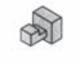
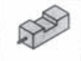
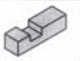
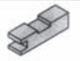
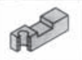
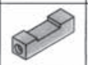
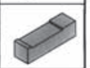
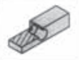
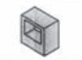
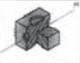
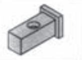
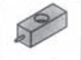
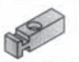
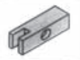
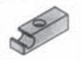
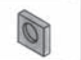
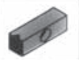
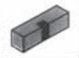
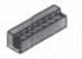
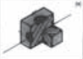
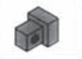
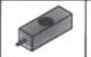
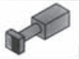
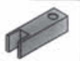
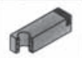
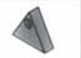
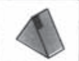


THIRD DIGIT

		Part is ALPHA symmetric (see note 5)			Part is not ALPHA symmetric [code the main feature or features causing ALPHA asymmetry] (see note 6)						
		Part has only one natural resting aspect or end and side surfaces can be readily distinguished by their shapes or dimensions (see note 7)	End and side surfaces can be distinguished because of steps, chamfers, holes or recesses	End and side surfaces can only be distinguished because of other features, features too small or slight asymmetry (see notes 8 and 12)	Steps or chamfers (see note 9)		Through grooves (see note 9)		Holes or recesses (cannot be seen in outer shape of silhouette)	Other geometric features	Slight asymmetry, features too small or non-geometric features [such as paint, lettering, etc.] (see notes 8 and 12)
					Part can be fed in slot and supported by large end or protruding flanges with center of mass below supporting surfaces and the part is not triangular (see note 10)	Part cannot be fed in slot and supported by large end or protruding flanges with center of mass below supporting surfaces or part is triangular	Can be seen in end view (see note 11)	Can be seen in side view (see note 11)			
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Part has 90° or 120° rotational symmetry about the principal axis (see notes 2, 3 and 4)	**0**										

Triangular and Square Parts (Parts with a first digit of 3, 4, or 5) (continued)



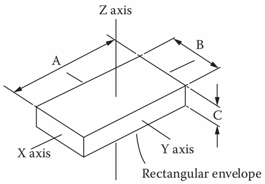
SECOND DIGIT				Part is ALPHA symmetric (see note 5)			Part is not ALPHA symmetric [code the main feature or features causing ALPHA asymmetry] (see note 6)						
				Code the same feature or features coded in the second digit		End and side surfaces can only be distinguished because of features too small or slight asymmetry (see notes 8 and 12)	Steps or chamfers provided by external features (see note 9)		Steps or chamfers provided by non-external features (see note 9)		Holes or recesses [cannot be seen in outer shape of silhouette]		Other features, slight asymmetry or features too small (see notes 8 and 12)
				Steps, chamfers or grooves can be seen in side view or other features on side surfaces (see note 9)	Steps, chamfers or grooves can be seen in end view or other features on end surfaces (see note 9)		Features on side surfaces (see note 15)	Features on end surfaces (see note 15)	Features on side surfaces (see note 15)	Features on end surfaces (see note 15)	On side surfaces (see note 15)	On end surfaces (see note 15)	
				0	1	2	3	4	5	6	7	8	9
Part has 180° rotational symmetry about the principal axis [code the main feature or features causing 180° rather than 90° rotational symmetry about the principal axis] (see notes 4 and 13)	Steps or chamfers can be seen in side or end views (see note 9)		1										
	Through grooves can be seen in side or end views (see note 9)		2										
	Holes or recesses [cannot be seen in outer shape of silhouette]		3										
	Other features, features too small or slight asymmetry (see notes 8 and 12)		4										
Part does not have 180° rotational symmetry about the principal axis [code the main feature or features causing rotational asymmetry] (see notes 4 and 14)	Steps or chamfers can be seen in side or end views (see note 9)	External to the envelope	5										
		Non-external	6										
	Through grooves can be seen in side or end views (see note 9)		7										
	Holes or recesses [cannot be seen in outer shape of silhouette]		8										
	Other features, features too small or slight asymmetry (see notes 8 and 12)		9										

Rectangular Parts (Parts with a first digit of 6, 7, or 8)

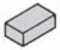
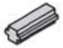
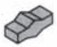
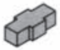
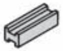
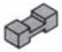
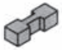
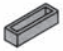
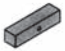
1. A part whose basic shape is a rectangular prism is called a rectangular part. The part is not difficult to feed.
2. 180 deg rotational symmetry about an axis means that the same orientation of the part will be repeated only once by rotating the part through 180 deg about that axis.
3. Part can be oriented without utilizing features other than the dimensions of the envelope.
4. Steps, chamfers or through grooves are features which result in a deviation of the silhouette of a part from the silhouette of its envelope.
5. If exposed features are prominent but the symmetry caused by these features is too small to be employed for orientation purposes, then the symmetry is said to be slight asymmetry. For a part with 180 deg rotational symmetry about a certain axis, slight asymmetry implies that the part is almost 90 deg rotationally symmetric about the same axis.
6. A feature is too small, if it is too small to be employed for orientation purposes.
7. A part having no rotational symmetry means that the same orientation of the part will not be repeated by rotating the part through any angle less than 360 deg about any one of the three axis X, Y, and Z. The X-axis is parallel to the longest side of the envelope, the Y-axis is parallel to the intermediate side and the Z-axis is parallel to the shortest side.
8. A main feature is a feature that is chosen to define the orientation of the part. All the features that are chosen to completely define the orientation of the part should be necessary and sufficient for the purpose.

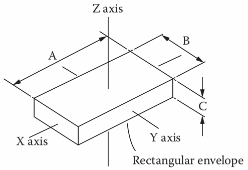
   Often, features arise in pairs or groups and the pair or group of features is symmetric about one of the three axis X, Y, and Z. In this case, the pair or group of features should be regarded as one feature. Using this convention, two main features at most are needed to completely define thed orientation of a part.
9. Sometimes, when a part has no rotational symmetry, its orientation can either be defined by one or by two main features. Under these circumstances the part code is determined by the following in decreasing order of preference:
   a. Choose one main feature, if it results in a third digit less than 5.
   b. Choose two main features if they result in a third digit less than 5.
   c. Choose one main feature, if it results in a third digit greater than 5.
   d. Choose two main features if they result in a third digit greater than 5.
10. The symmetric plane is the plane that divides the part into halves that are mirror images of each other.

Rectangular Parts (Parts with a first digit of 6, 7, or 8)

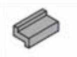
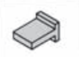
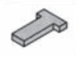
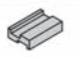
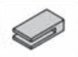
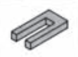
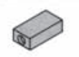
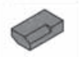
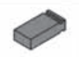
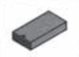
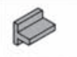
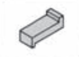
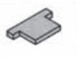
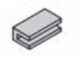
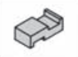
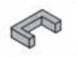
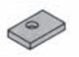
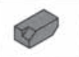
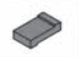
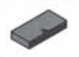
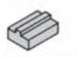
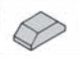
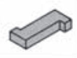
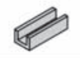
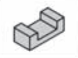
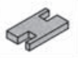
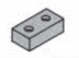
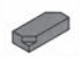
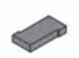
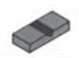
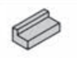
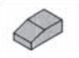
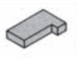
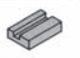
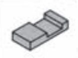
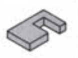
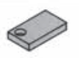
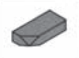
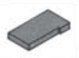
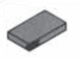
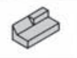
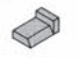
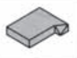
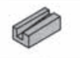
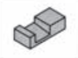
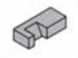
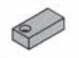
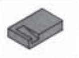
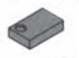
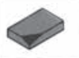
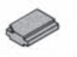
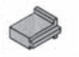
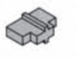
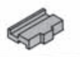
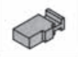
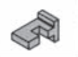
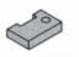
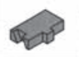
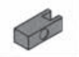
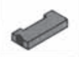
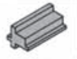
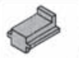
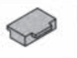
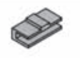
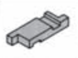
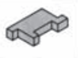
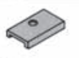
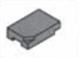
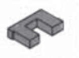
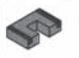
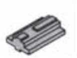
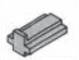
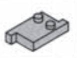
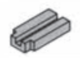
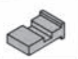
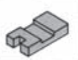
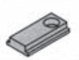
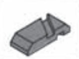
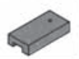
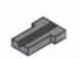
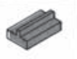
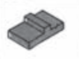
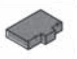
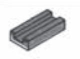
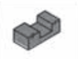
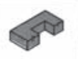
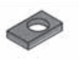
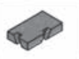
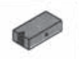
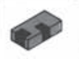


THIRD DIGIT

		Three adjacent surfaces of the envelope have significant differences in dimensions (see note 3)	Two or more adjacent surfaces of the envelope have similar dimensions [code the main feature or features which distinguish the adjacent surfaces having similar dimensions]								
			Steps or chamfers (see note 4)			Through grooves (see note 4)			Holes or recesses (cannot be seen in outer shape of silhouette)	Slight asymmetry or features too small (see notes 5 and 6)	Other geometric features or non-geometric features (such as paint, lettering, etc.)
			Parallel to X axis	Parallel to Y axis	Parallel to Z axis	Parallel to X axis	Parallel to Y axis	Parallel to Z axis			
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Part has 180° rotational symmetry about all three axes (see note 2)	**0**										



SECOND DIGIT

					Code the main feature [code the feature that gives largest third digit, if more than one feature is utilized to define the orientation of the part] (see note 8)									
					Steps or chamfers (see note 4)			Through grooves (see note 4)			Holes or recesses [cannot be seen in outer shape of silhouette]	Other geometric features	Features too small (see note 6)	Non- geometric features [such as paint, lettering, etc.]
					Parallel to X axis	Parallel to Y axis	Parallel to Z axis	Parallel to X axis	Parallel to Y axis	Parallel to Z axis				
					0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Part has 180° rotational symmetry about one axis only (see note 2)	About X axis			**1**										
	About Y axis			**2**										
	About Z axis			**3**										
Part has no rotational symmetry [code the main feature or features that can completely define the orientation] (see notes 7 and 8)	Part has no slight asymmetry and its orientation can be defined by one main feature only or by two main features at least one of which is a step, chamfer or through groove or group of such features (see note 5)	Part's orientation is defined by one main feature only (see note 90	Part has a symmetric plane (see note 10)	**4**										
			Part has no symmetric plane (see note 10)	**5**										
		Part's orientation is defined by two main features and at least one of them is a step, chamfer or through groove or a group of such features (see note 9)	One feature is symmetric about X axis and the other one is symmetric about Y axis	**6**										
			One feature is symmetric about Y axis and the other one is symmetric about Z axis	**7**										
			One feature is symmetric about Z axis and the other one is symmetric about X axis	**8**										
	Part has slight asymmetry about at least one of its axes or the orientation of the part can only be defined by two main features neither of which are steps, chamfers or through grooves (see notes 5 and 8)			**9**										

Difficult-to-Feed Parts (parts with a first digit of 9)

Flexible. A part is considered flexible if the part cannot maintain its shape under the action of automatic feeding so that orienting devices cannot function satisfactorily.

Delicate. A part is considered delicate if damage may occur during handling, either due to breakage caused by parts falling from orienting sections or tracks onto the hopper base, or due to wear caused by recirculation of parts in the hopper. When wear is the criterion, a part would be considered delicate if it could not recirculate in the hopper for 30 min and maintain the required tolerance.

Sticky. If a force, comparable to the weight of a nontangling or nonnesting part, is required to separate it from bulk, the part is considered sticky.

Light. A part is considered too light to be handled by conventional hopper feeders if the ratio of its weight to the volume of its envelope is less than 1.5kN/m^3.

Overlap. Parts will tend to overlap in a feeder when an alignment of better than 0.2 mm is required to prevent shingling or overlapping during feeding in single file on a horizontal track.

Large. A part is considered to be too large to be readily handled by conventional hopper feeders when its smallest dimension is greater than 50 mm or if its maximum dimension is greater than 150 mm. A part is considered to be too large to be handled by a particular vibratory hopper feeder if $L > d/8$, where L is the length of the part measured parallel to the feeding direction and d is the feeder or bowl diameter.

Very small. A part is considered to be too small to be readily handled by conventional hopper feeders when its largest dimension is less than 3 mm. A part is considered to be too small to be readily handled by a particular vibratory hopper feeder if its largest dimension is less than the radius of the curved surface joining the hopper wall and the track surface measured in a plane perpendicular to the feeding direction.

Nest. Parts are considered to nest if they interconnect when in bulk causing orientation problems. No force is required to separate the parts when they are nested.

Severely nest. Parts are considered to severely nest if they interconnect and lock when in bulk and require a force to separate them.

Tangle. Parts are said to tangle if a reorientation is required to separate them when in bulk.

Severely tangle. Parts are said to severely tangle if they require manipulation to specific orientations and a force is required to separate them.

Abrasive. A part is considered to be abrasive if it may cause damage to the surface of the hopper feeding device unless these surfaces are specially treated.

Difficult-to-Feed Parts (parts with a first digit of 9)

THIRD DIGIT

SECOND DIGIT					Parts will not tangle or nest				Parts will tangle or nest but not severely				Parts will severely nest but not severely tangle	Parts will severely tangle
					Not light		Light		Not light		Light			
					Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky		
					0	1	2	3	4	5	6	7	8	9
Parts are small and non-abrasive	Parts do not tend to overlap during feeding	Not delicate	Non-flexible	0	Incorrect choice of first digit									
			Flexible	1										
		Delicate	Non-flexible	2										
			Flexible	3										
	Parts tend to overlap during feeding	Not delicate	Non-flexible	4										
			Flexible	5										
		Delicate	Non-flexible	6										
			Flexible	7										

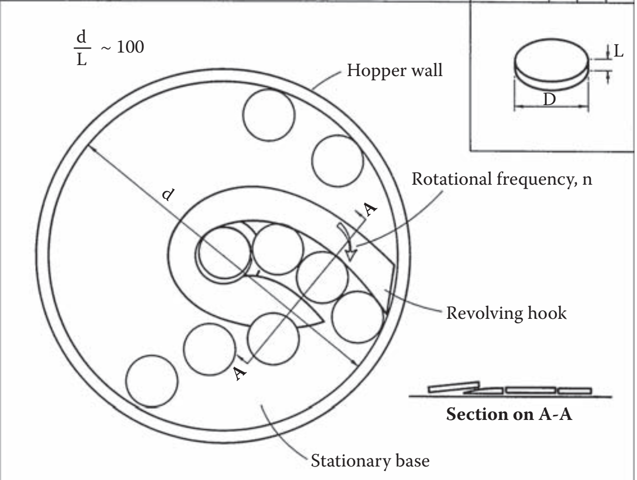
		Very small parts					Large parts				
		Rotational parts		Non-rotational parts			Rotational parts		Non-rotational parts		
For definitions of these terms and dimensions see code sheet – choice of first digit		Discs or short cylinders $L/D \leq 1.5$	Long cylinders $L/D > 1.5$	Flat parts $A/B \leq 3$ $A/C > 4$	Long parts $A/B > 3$	Cubic parts $A/B \leq 3$ $A/B \leq 4$	Discs or short cylinders $L/D \leq 1.5$	Long cylinders $L/D > 1.5$	Flat parts $A/B \leq 3$ $A/C > 4$	Long parts $A/B > 3$	Cubic parts $A/B \leq 3$ $A/C \leq 4$
		0	1	2	3	4	5	6	7	8	9
Parts are very small or large but are non-abrasive	8										

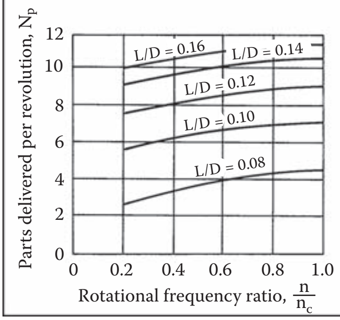
		Parts will not severely tangle or nest									Parts will severely tangle or nest
		Small parts					Large parts		Very small parts		
		Part's orientation is defined by geometric feature(s) alone			Part's orientation is not defined by geometric feature(s) alone		Part's orientation is defined by geometric feature(s) alone	Part's orientation is not defined by geometric feature(s) alone	Part's orientation is defined by geometric feature(s) alone	Part's orientation is not defined by geometric feature(s) alone	
		Non-flexible		Flexible							
		Parts do not tend to overlap during feeding	Parts tend to overlap during feeding		Parts do not tend to overlap during feeding	Parts tend to overlap during feeding					
		0	1	2	3	4	5	6	7	8	9
Abrasive parts	9										

D.2 Feeding and Orienting Techniques

Data sheets showing feeding and orienting techniques catalogued under part codes.

REVOLVING HOOK HOPPER FEEDER	PART CODE	0	0	0





Feed rate = $N_p \times n$

where:

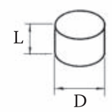
N_p = Parts delivered per revolution

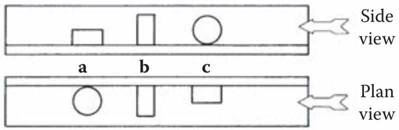
n = Rotational frequency of hook

n_c = Critical rotational frequency of the hook (See section D4)

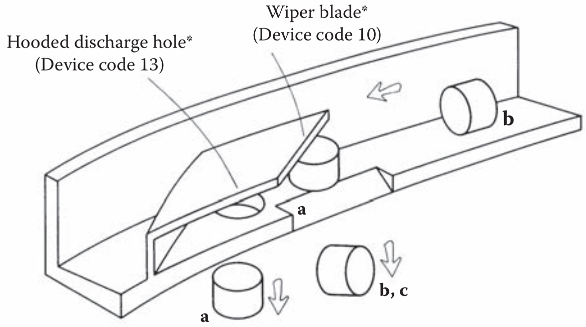
VIBRATORY BOWL FEEDER

PART CODE	0	0	0





Part orientations

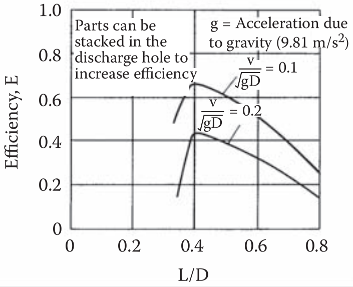

Hooded discharge hole* (Device code 13)
Wiper blade* (Device code 10)
a
b
b, c
a

Feed rate = $\frac{v}{D} \times E$

where:

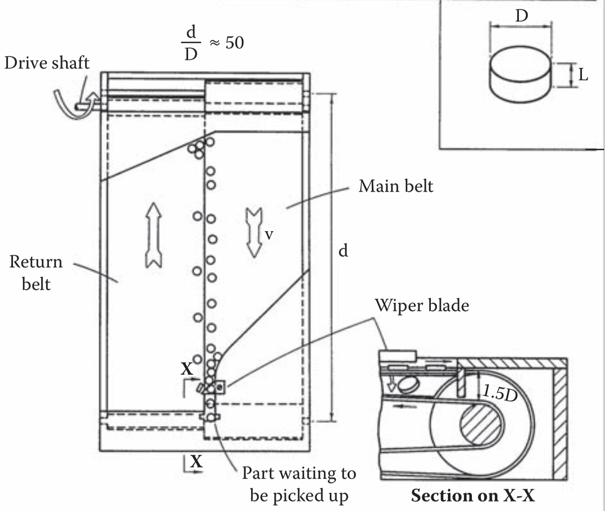
v = Conveying velocity

E = Efficiency

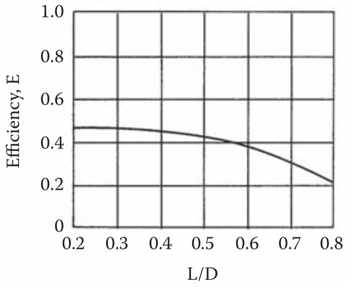


HORIZONTAL BELT FEEDER

PART CODE	0	0	1



Section on X-X



Feed rate = $\frac{v}{D} \times E$

where:

v = Main belt velocity

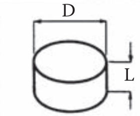
E = Efficiency

D = Part diameter

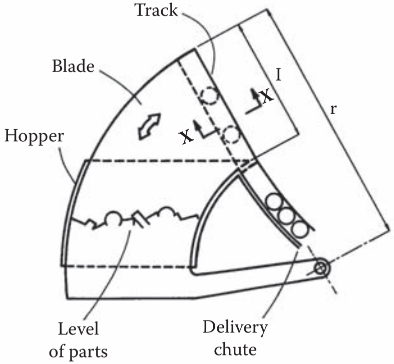
Load > 100 parts

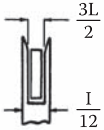
CENTERBOARD HOPPER FEEDER

CENTERBOARD HOPPER FEEDER	PART CODE	0	0	1

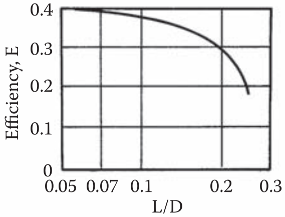


$\frac{I}{L} \sim 50 \quad \frac{I}{r} = 0.5$





Enlarged section on X-X



Feed rate $= E \times N_t \times n$

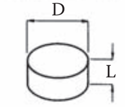
$E = \text{Efficiency} = \frac{\text{Number of parts fed per reciprocation}}{\text{Track capacity, } N_t}$

N_t = Track capacity = Maximum number of parts that can fit in track

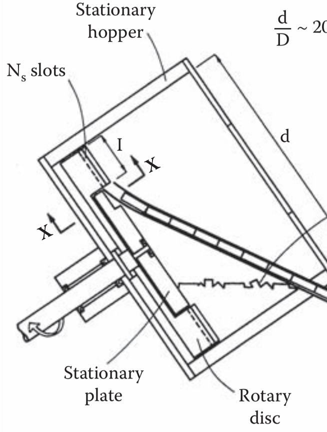
n = Frequency of blade reciprocation

ROTARY DISC HOPPER FEEDER

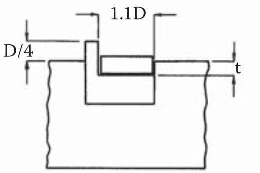
ROTARY DISC HOPPER FEEDER	PART CODE	0	0	1



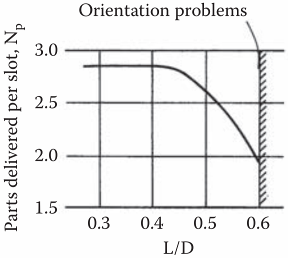
$\frac{d}{D} \sim 20; \quad \frac{I}{D} = 3.5$



L/2 < t < L



Enlarged section on X-X



Feed rate $= N_p \times N_s \times n$

where:

N_p = Parts delivered per slot

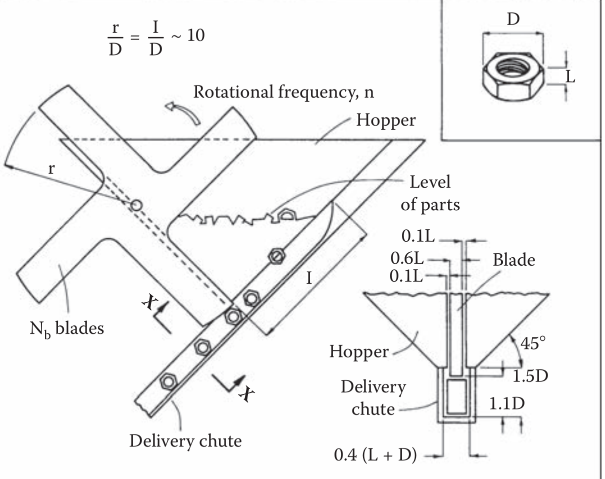
N_s = Number of slots

n = Rotational frequency of disc

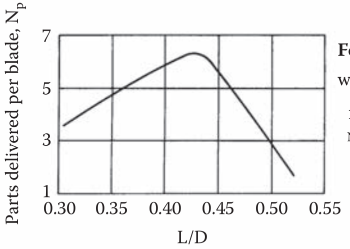
BLADED WHEEL HOPPER FEEDER

PART CODE 0 0 1

$\frac{r}{D} = \frac{I}{D} \sim 10$



Enlarged view on X-X



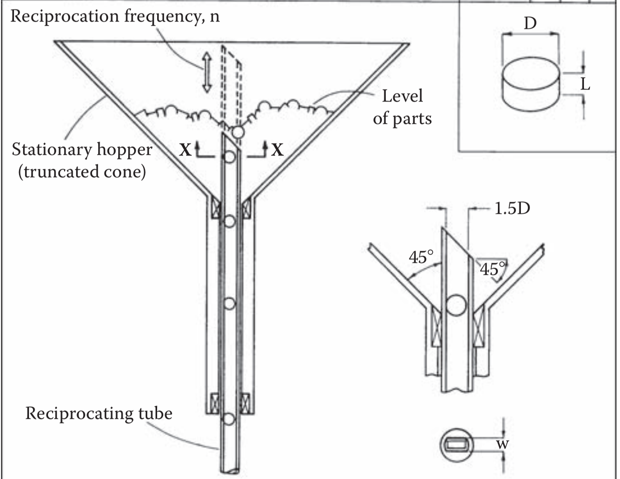
Feed rate = $N_p \times N_b \times n$

where:

N_p = Parts delivered per blade
N_b = Number of blades
n = Rotational frequency of wheel

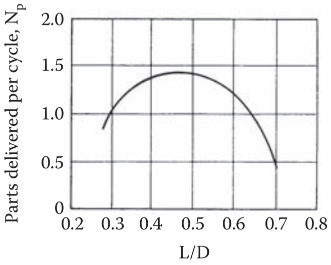
RECIPROCATING TUBE HOPPER FEEDER

PART CODE 0 0 1


Reciprocation frequency, n
D
L
Level of parts
Stationary hopper (truncated cone)
X
X
1.5D
45°
45°
Reciprocating tube
w

Enlarged section on X-X

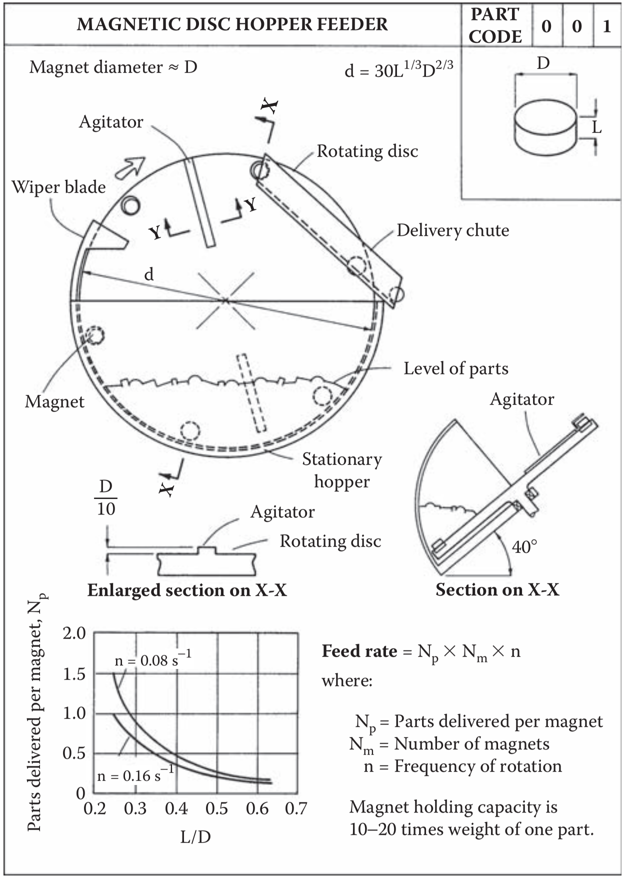
For L/D ≤ 0.5 w = 1.5L
For L/D > 0.5 w = 1.4L



Feed rate = $N_p \times n$

where:

N_p = Parts delivered per cycle
n = Frequency of reciprocation

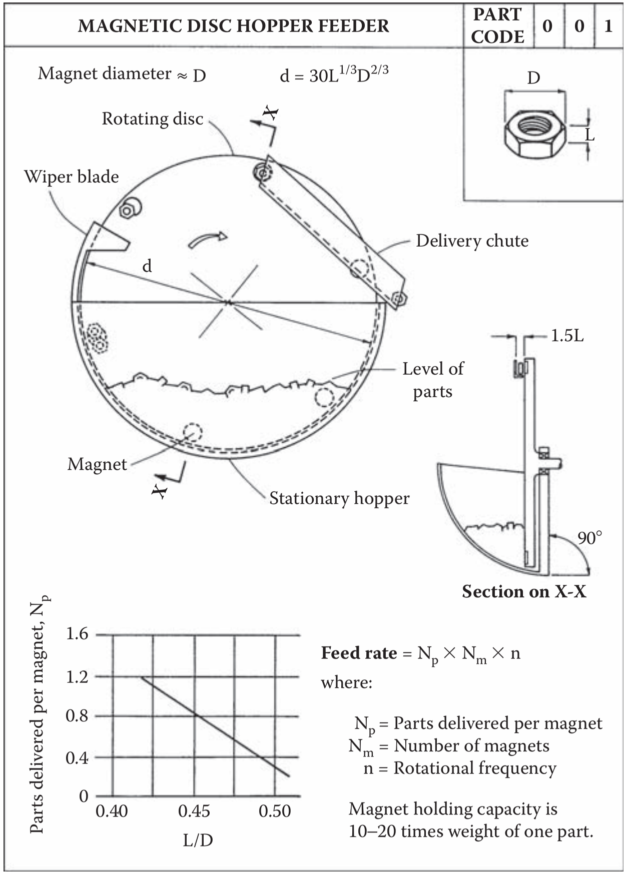


Feed rate = $N_p \times N_m \times n$

where:

N_p = Parts delivered per magnet
N_m = Number of magnets
n = Frequency of rotation

Magnet holding capacity is 10–20 times weight of one part.



Feed rate = $N_p \times N_m \times n$

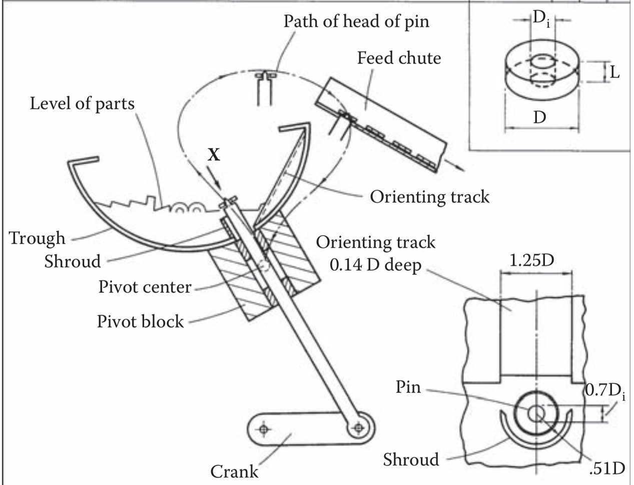
where:

N_p = Parts delivered per magnet
N_m = Number of magnets
n = Rotational frequency

Magnet holding capacity is 10–20 times weight of one part.

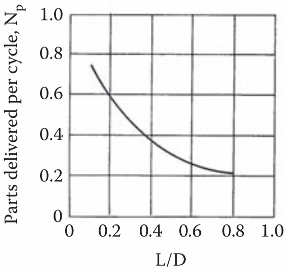
ROCKING TROUGH HOPPER FEEDER

PART CODE 0 0 1



View on arrow X

Head of the pin is designed to accept only one part



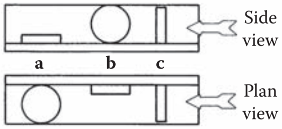
Feed rate = $N_p \times n$

where:

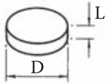
N_p = Parts delivered per cycle
n = Rotational frequency

VIBRATORY BOWL FEEDER

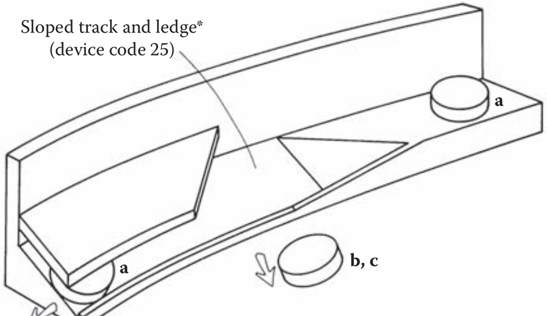
PART CODE 0 0 1



Part orientations



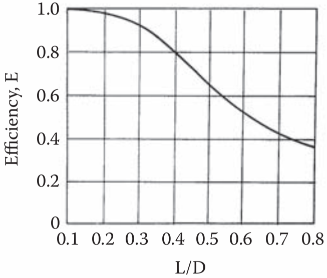
Note: Wiper blade (device code 10) Required with L/D ≥ 0.7



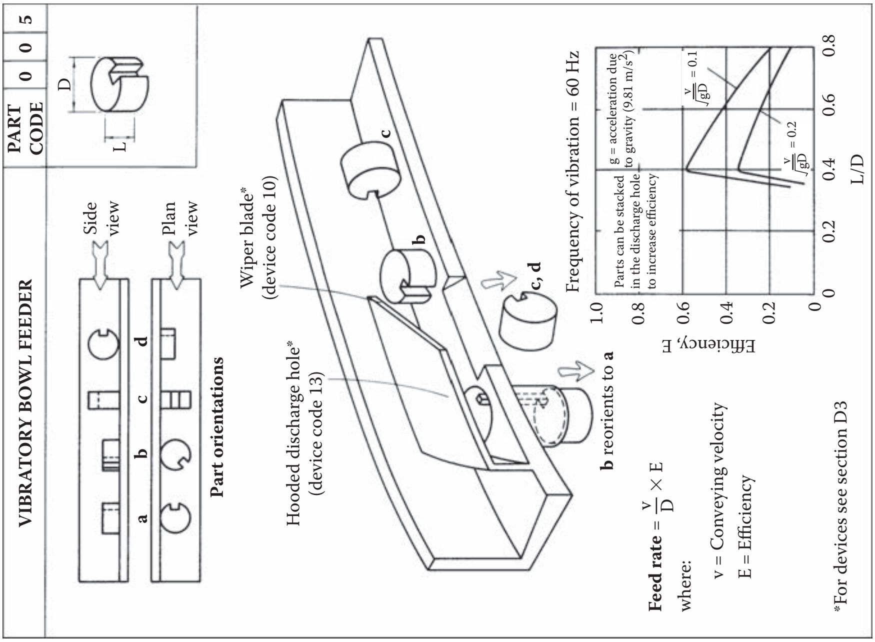
Feed rate = $\frac{v}{D} \times E$

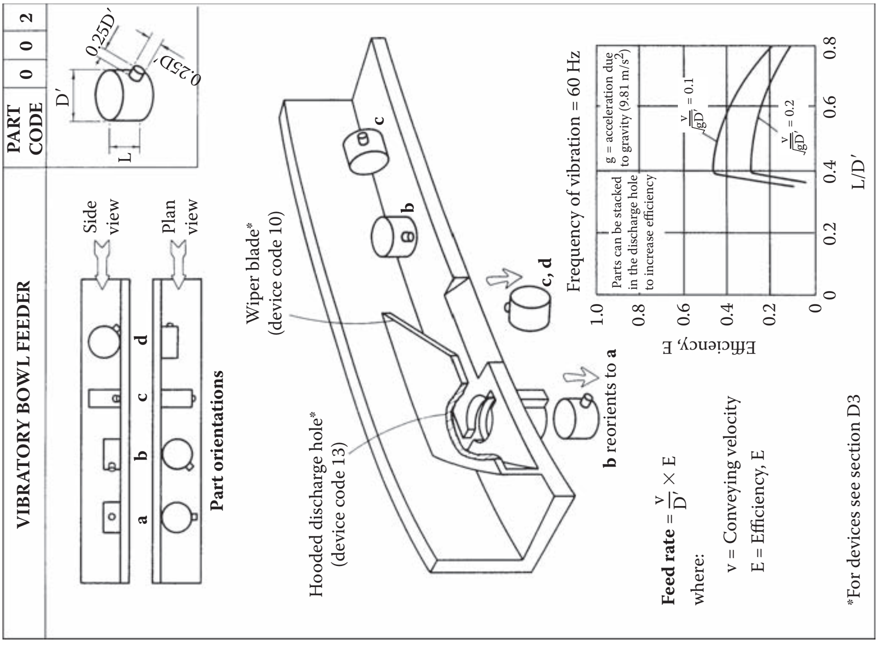
where:

v = Conveying velocity
E = Efficiency



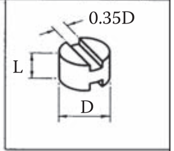
*For devices see section D4

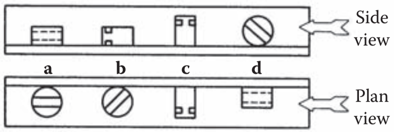

VIBRATORY BOWL FEEDER
PART CODE
0 0 5
D
L
Side view
Plan view
a
b
c
d
Part orientations
Wiper blade* (device code 10)
Hooded discharge hole* (device code 13)
c
b
c, d
b reorients to a
Frequency of vibration = 60 Hz
Parts can be stacked in the discharge hole to increase efficiency
g = acceleration due to gravity (9.81 m/s^2)
$\frac{v}{\sqrt{gD}} = 0.1$
$\frac{v}{\sqrt{gD}} = 0.2$
Efficiency, E
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
L/D
Feed rate = $\frac{v}{D} \times E$
where:
v = Conveying velocity
E = Efficiency
*For devices see section D3


VIBRATORY BOWL FEEDER
PART CODE
0 0 2
D′
L
0.25D′
0.25D′
Side view
Plan view
a
b
c
d
Part orientations
Wiper blade* (device code 10)
Hooded discharge hole* (device code 13)
c
b
c, d
b reorients to a
Frequency of vibration = 60 Hz
Parts can be stacked in the discharge hole to increase efficiency
g = acceleration due to gravity (9.81 m/s^2)
$\frac{v}{\sqrt{gD'}} = 0.1$
$\frac{v}{\sqrt{gD'}} = 0.2$
Efficiency, E
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
L/D′
Feed rate = $\frac{v}{D'} \times E$
where:
v = Conveying velocity
E = Efficiency, E
*For devices see section D3

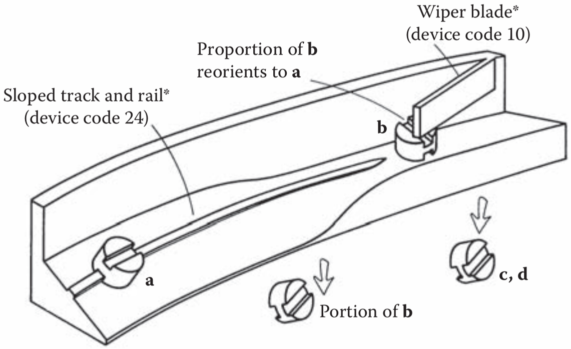
VIBRATORY BOWL FEEDER

PART CODE	0	0	6





Part orientations

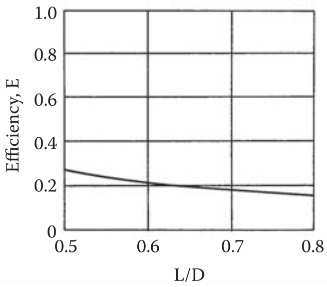


Feed rate = $\frac{v}{D} \times E$

where:

v = Conveying velocity

E = Efficiency

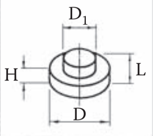


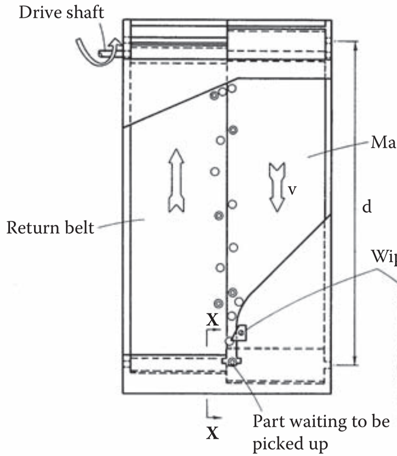
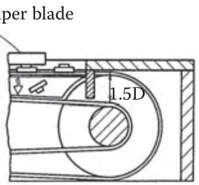
*For devices see section D3

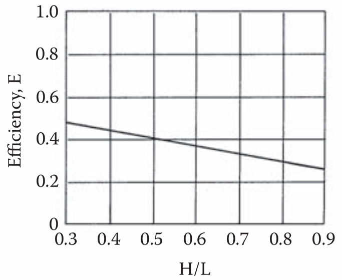
HORIZONTAL BELT FEEDER

PART CODE	0	2	1

$\frac{L}{D} = 0.5 \quad \frac{D_1}{D} = 0.5 \quad \frac{d}{D} \approx 50$





Feed rate = $\frac{v}{D} \times E$

where:

v = Main belt velocity

E = Efficiency

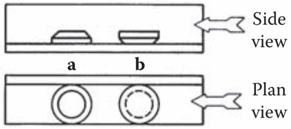
D = Part diameter

Load > 90 parts

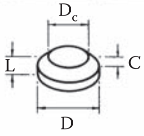
VIBRATORY BOWL FEEDER	PART CODE	0	2	1

$\frac{C}{L} = 0.5$

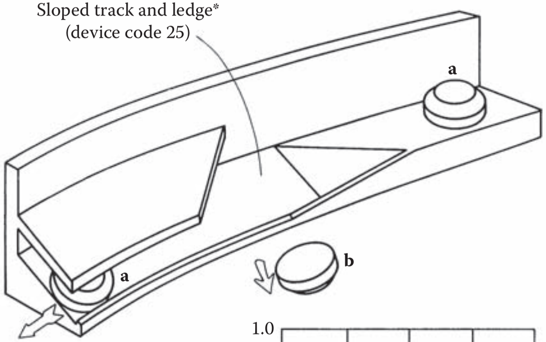
$D_C = D - 2C$

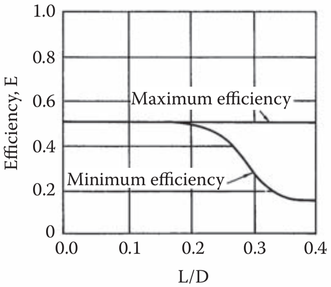


Part orientations



Sloped track and ledge*
(device code 25)





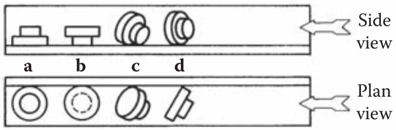
Feed rate = $\frac{v}{D} \times E$

where:

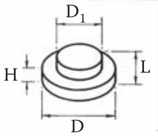
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	0	2	1

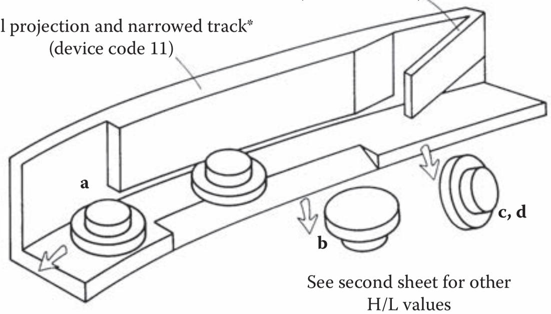


Part orientations

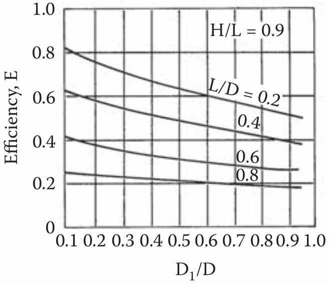


Wiper blade*
(device code 10)

Wall projection and narrowed track*
(device code 11)



See second sheet for other H/L values



Feed rate = $\frac{v}{D} \times E \times P$

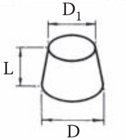
where:

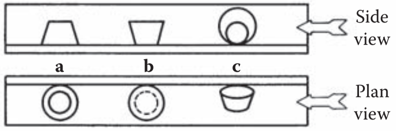
v = Conveying velocity
E = Efficiency
P = Probability that orientation **a** will pass the wall projection device (see section D3 device code 11)

*For devices see section D3

VIBRATORY BOWL FEEDER

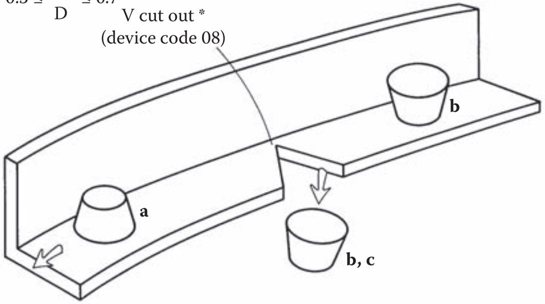
PART CODE	0	2	1





Part orientations

$$0.3 \le \frac{D_1}{D} \le 0.7$$

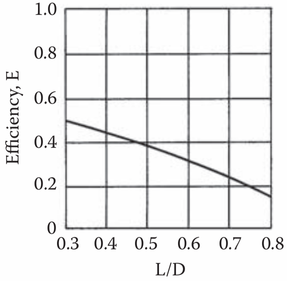


Feed rate = $\frac{v}{D} \times E$

where:

v = Conveying velocity

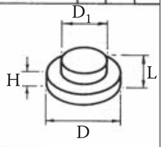
E = Efficiency

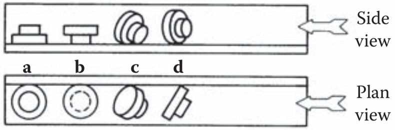


*For devices see section D3

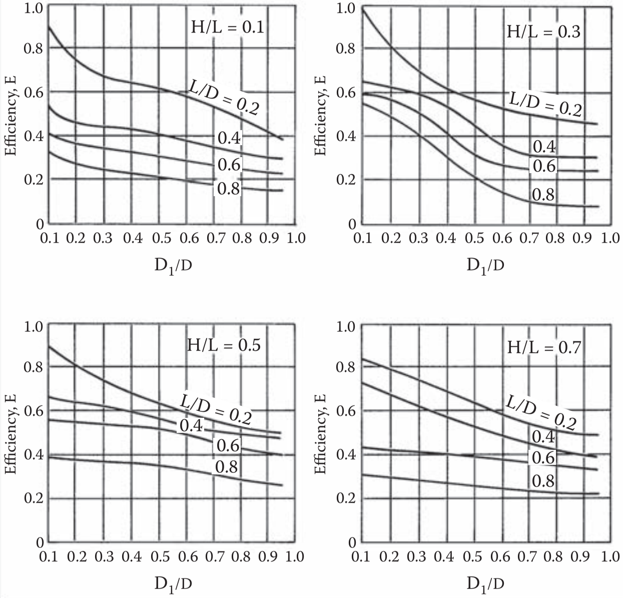
VIBRATORY BOWL FEEDER (Continued)

PART CODE	0	2	1



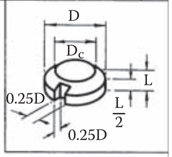


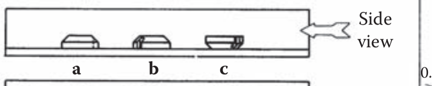
Part orientations



VIBRATORY BOWL FEEDER

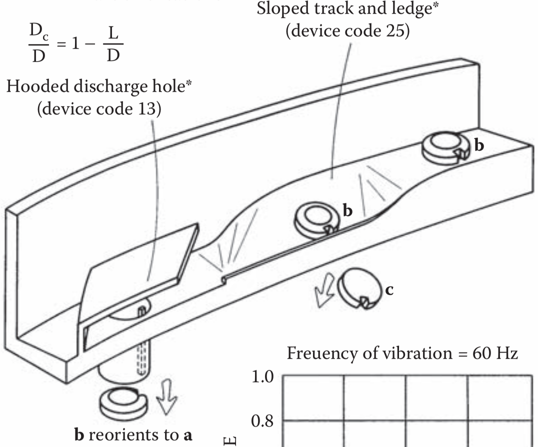
PART CODE **0 2 5**



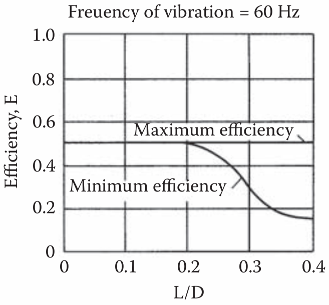


Part orientations

$$\frac{D_c}{D} = 1 - \frac{L}{D}$$


Hooded discharge hole* (device code 13)
Sloped track and ledge* (device code 25)
b
b
c

b reorients to **a**



Feed rate = $\frac{v}{D} \times E$

where:

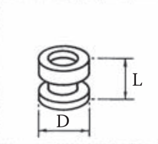
v = Conveying velocity

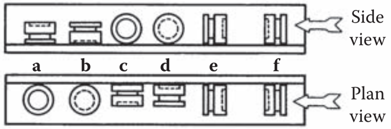
E = Efficiency

*For devices see section D3

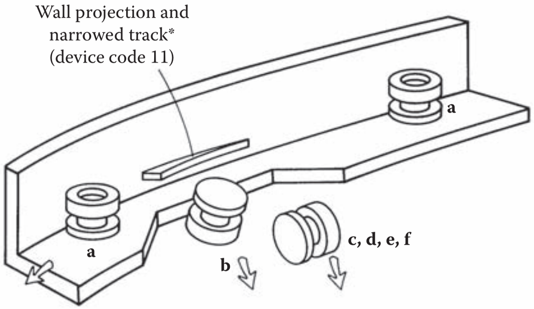
VIBRATORY BOWL FEEDER

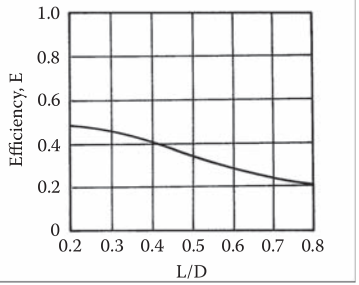
PART CODE **0 3 1**





Part orientations





Feed rate = $\frac{v}{L} \times E$

where:

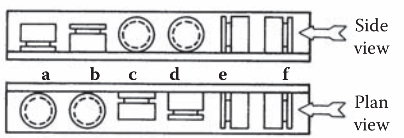
v = Conveying velocity

E = Efficiency

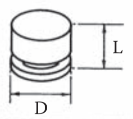
*For devices see section D3

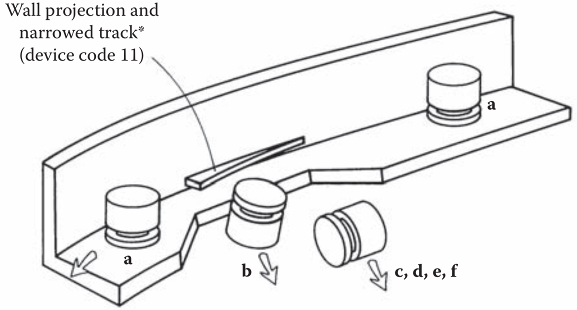
VIBRATORY BOWL FEEDER

PART CODE	0	4	1



Part orientations

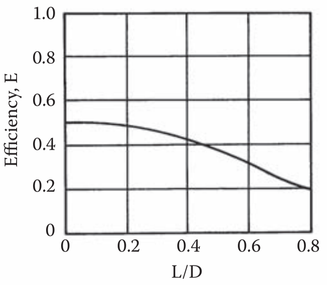




Feed rate = $\frac{v}{D} \times E$

where:

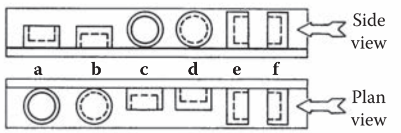
v = Conveying velocity
E = Efficiency



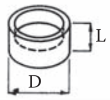
*For devices see section D3

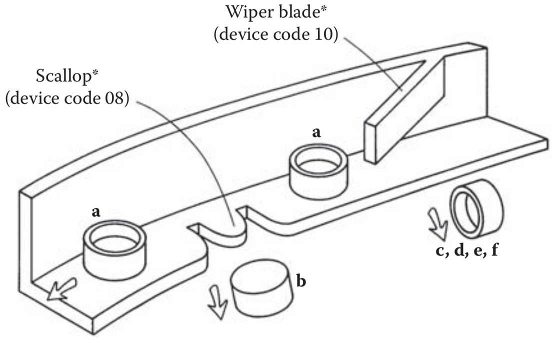
VIBRATORY BOWL FEEDER

PART CODE	0	5	1



Part orientations

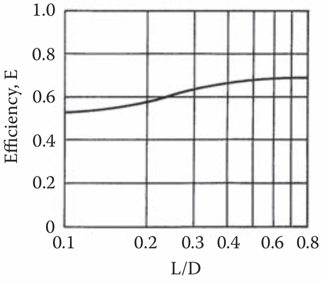




Feed rate = $\frac{v}{D} \times E$

where:

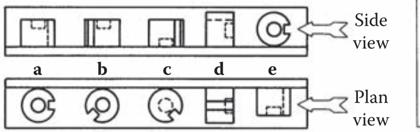
v = Conveying velocity
E = Efficiency



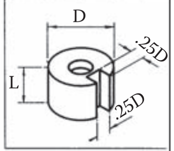
*For devices see section D3

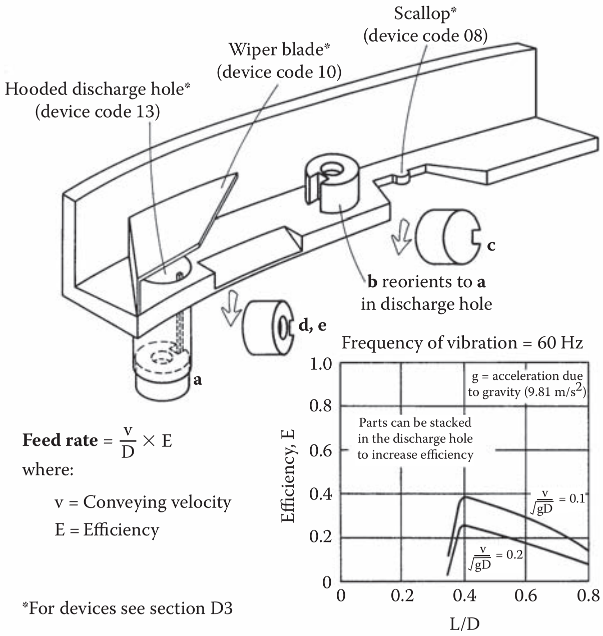
VIBRATORY BOWL FEEDER

PART CODE 0 5 5



Part orientations





Feed rate = $\frac{v}{D} \times E$

where:

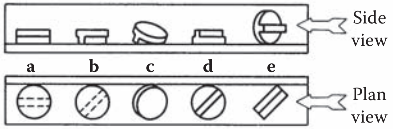
v = Conveying velocity

E = Efficiency

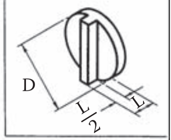
*For devices see section D3

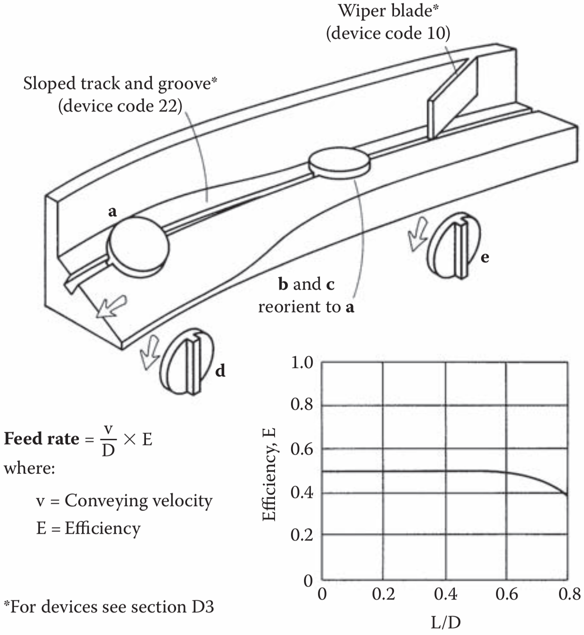
VIBRATORY BOWL FEEDER

PART CODE 0 7 3



Part orientations





Feed rate = $\frac{v}{D} \times E$

where:

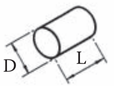
v = Conveying velocity

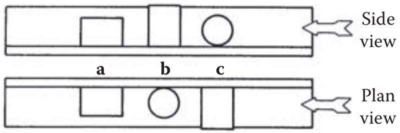
E = Efficiency

*For devices see section D3

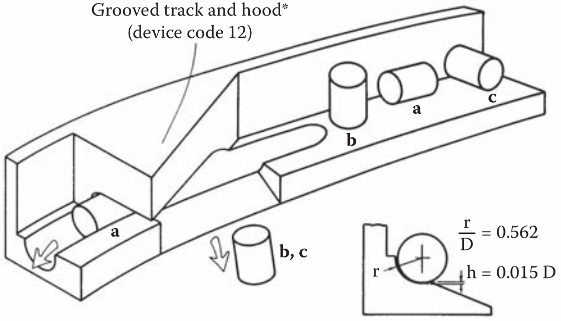
VIBRATORY BOWL FEEDER

PART CODE	1	0	0





Part orientations

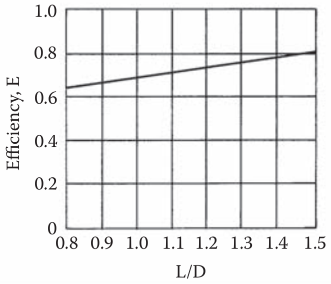


Feed rate $= \frac{v}{L} \times E$

where:

v = Conveying velocity

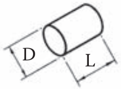
E = Efficiency

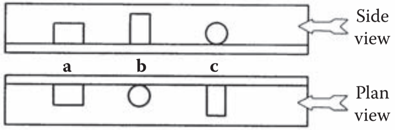


*For devices see section D3

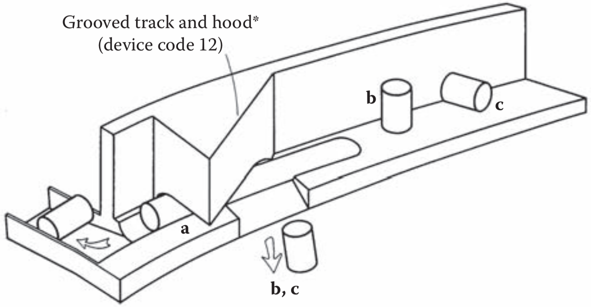
VIBRATORY BOWL FEEDER

PART CODE	1	0	1





Part orientations

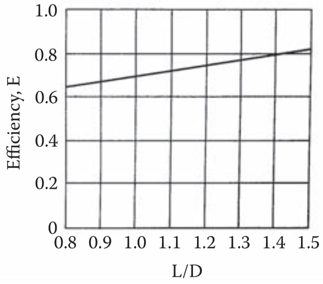


Feed rate $= \frac{v}{L} \times E$

where:

v = Conveying velocity

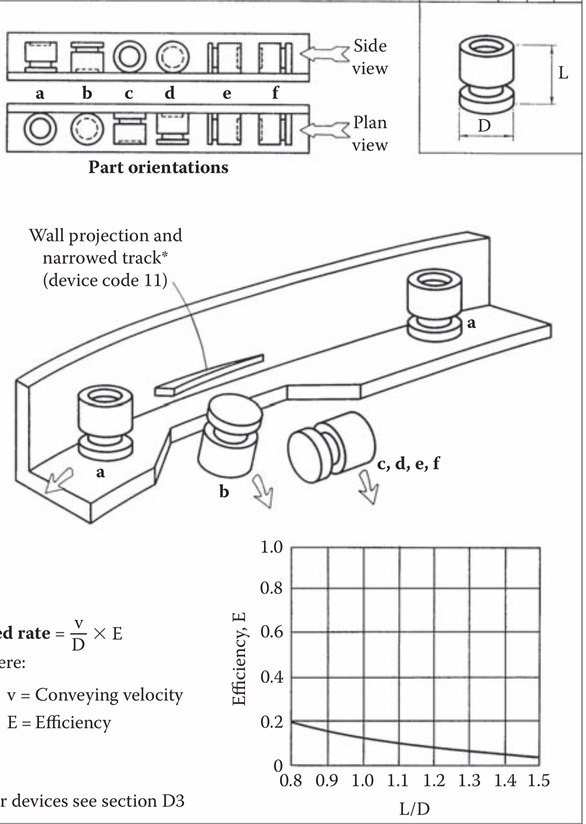
E = Efficiency



*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE	1	3	1



Feed rate = $\frac{v}{D} \times E$

where:

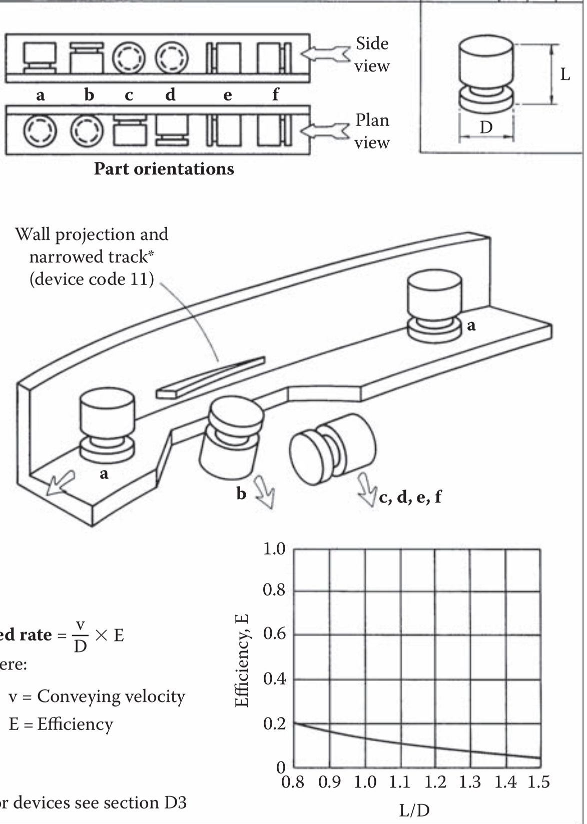
v = Conveying velocity

E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE	1	4	1



Feed rate = $\frac{v}{D} \times E$

where:

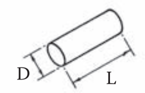
v = Conveying velocity

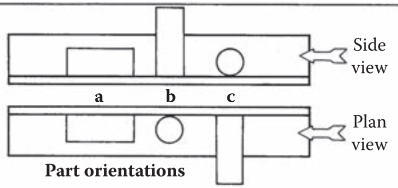
E = Efficiency

*For devices see section D3

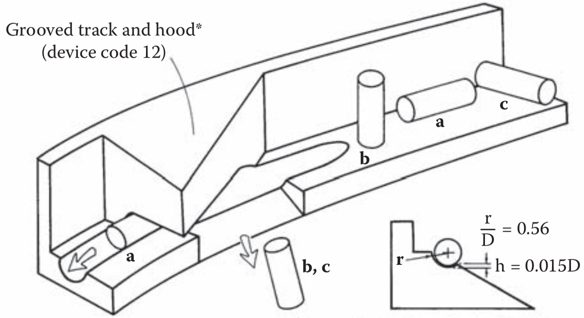
VIBRATORY BOWL FEEDER

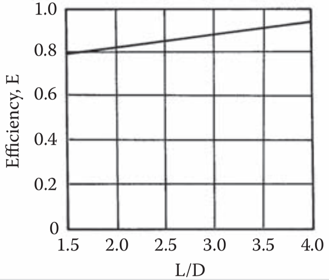
PART CODE	2	0	0





Part orientations





Feed rate = $\frac{v}{L} \times E$

where:

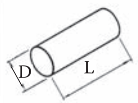
v = Conveying velocity

E = Efficiency

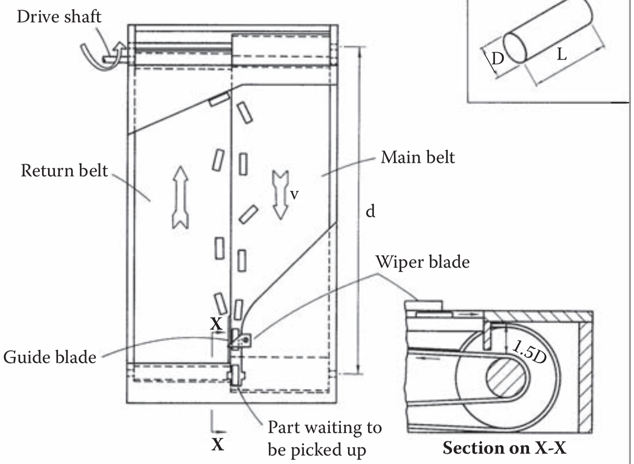
*For devices see section D3

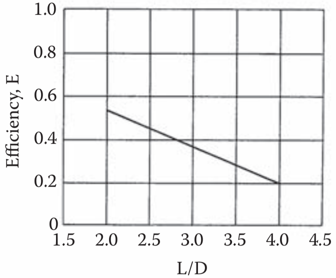
HORIZONTAL BELT FEEDER

PART CODE	2	0	0



$\frac{d}{D} \approx 50$





Feed rate = $\frac{v}{L} \times E$

where:

v = Main belt velocity

E = Efficiency

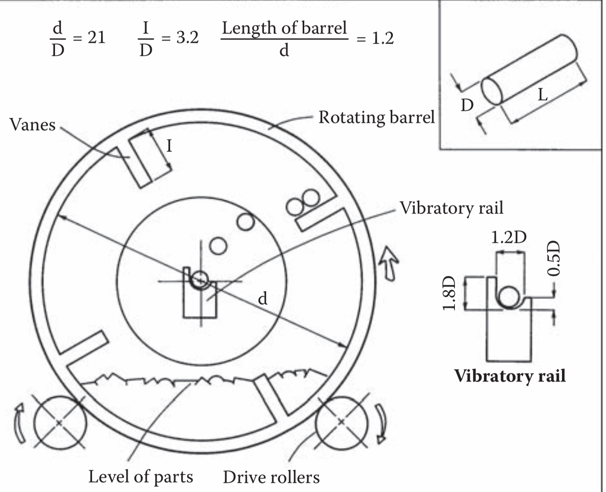
L = Part length

Load > 80 parts

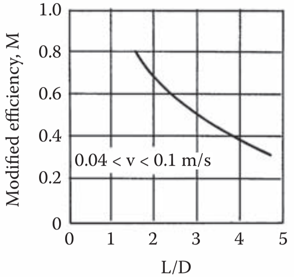
TUMBLING BARREL HOPPER FEEDER

PART CODE 2 0 0

$\frac{d}{D} = 21$ $\frac{I}{D} = 3.2$ $\frac{\text{Length of barrel}}{d} = 1.2$



Vibratory rail



Feed rate = $\frac{M \times v}{L} + 0.7$ parts/s

where:

M = Modified efficiency

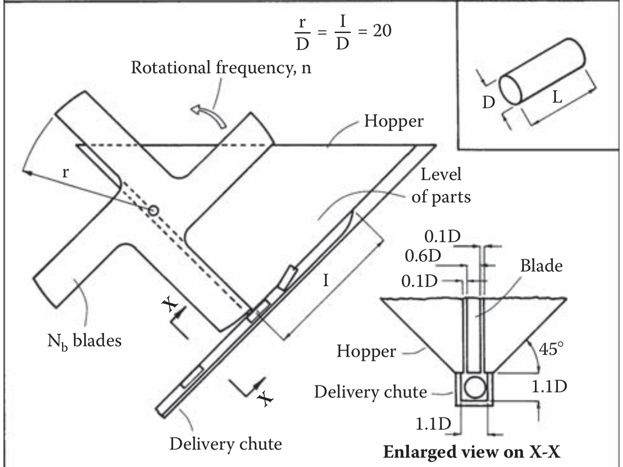
v = Conveying velocity on vibratory rail, m/s

L = Part length, m

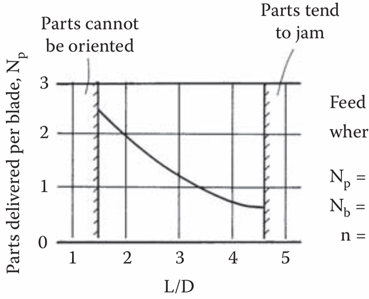
BLADED WHEEL HOPPER FEEDER

PART CODE 2 0 0

$\frac{r}{D} = \frac{I}{D} = 20$



Enlarged view on X-X



Feed rate = $N_p \times N_b \times n$

where

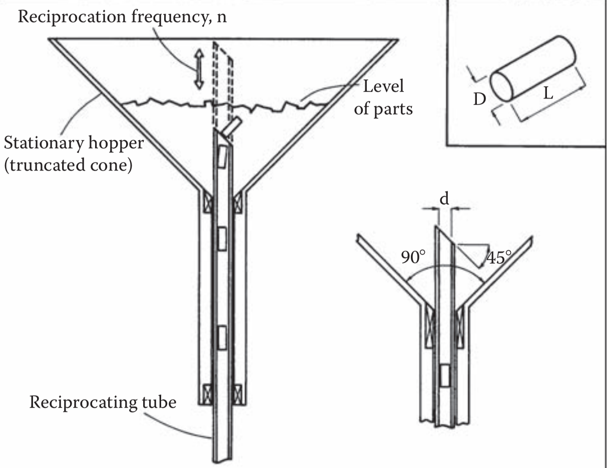
N_p = Parts delivered per blade

N_b = Number of blades

n = Rotational frequency of wheel

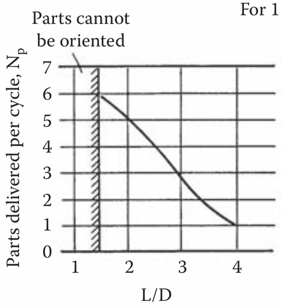
RECIPROCATING TUBE HOPPER FEEDER

PART CODE **2 0 0**


Reciprocation frequency, n
Level of parts
Stationary hopper (truncated cone)
Reciprocating tube
d
90°
45°
D
L

For L/D > 2 d = 2D

For 1.5 ≤ L/D ≤ 2 $d = 0.95\sqrt{L^2 + D^2}$



Feed rate = $N_p \times n$

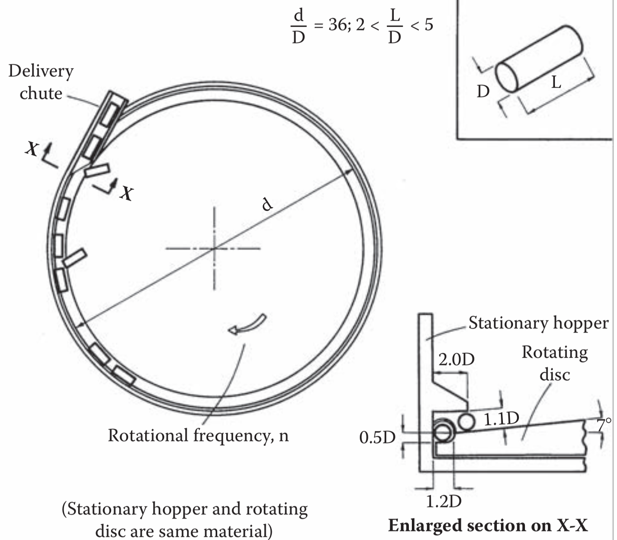
where

N_p = Parts delivered per cycle

n = Frequency of reciprocation

CENTRIFUGAL HOPPER FEEDER

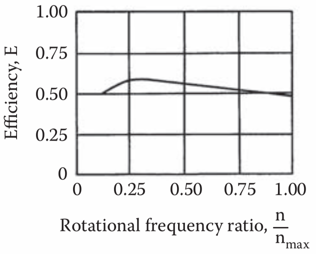
PART CODE **2 0 0**



$\frac{d}{D} = 36; 2 < \frac{L}{D} < 5$

Enlarged section on X-X

(Stationary hopper and rotating disc are same material)



Feed rate = $\frac{M \times \pi \times d \times n}{L}$

where:

E = Efficiency

d = Hopper diameter

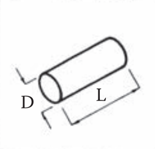
n = Rotational frequency of disc

L = Part length

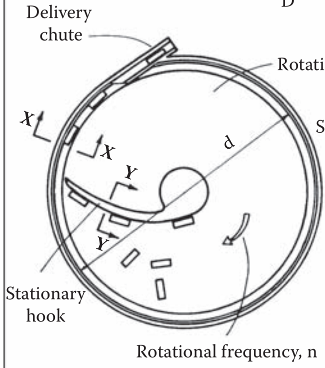
n_{max} = Maximum rotational frequency of the disc (from section D4)

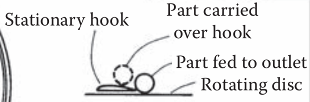
STATIONARY HOOK HOPPER FEEDER

PART CODE	2	0	0

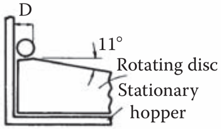


$\frac{d}{D} = 36$

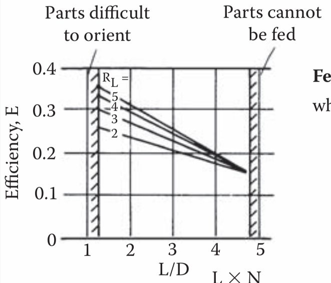




Enlarged section on Y-Y



Enlarged section on X-X



R_L = load ratio = $\frac{L \times N}{\pi \times d}$

Where N = number of parts in hopper

Feed rate = $\frac{E \times \pi \times d \times n}{L}$

where:

E = Efficiency

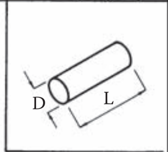
d = Hopper diameter

n = Rotational frequency of disc

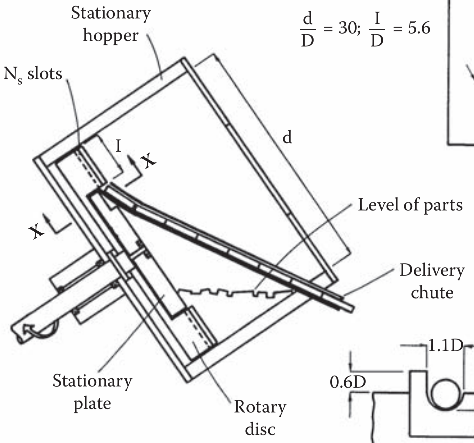
L = Part length

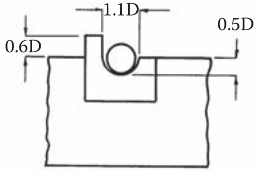
ROTARY DISC HOPPER FEEDER

PART CODE	2	0	0

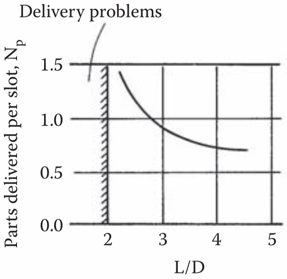


$\frac{d}{D} = 30; \frac{I}{D} = 5.6$





Enlarged section on X-X



Feed rate = $N_p \times N_s \times n$

where

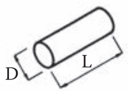
N_p = Parts delivered per slot

N_s = Number of slots

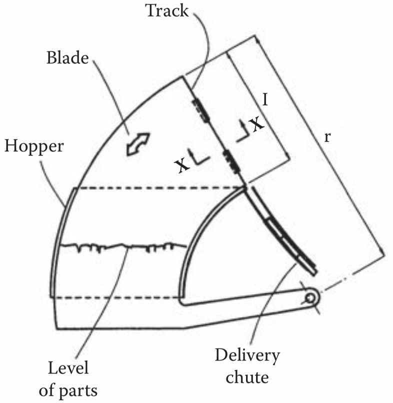
n = Rotational frequency of disc

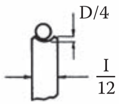
CENTERBOARD HOPPER FEEDER

PART CODE	2	0	0

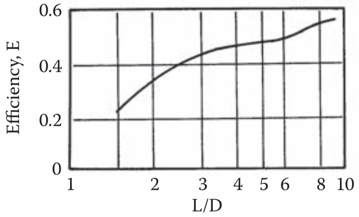


$\frac{I}{D} = 19;\ \frac{I}{r} = 0.5$





Enlarged section on X-X



Feed rate = E × N_t × n

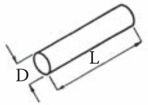
E = Efficiency = $\frac{\text{Number of parts fed per reciprocation}}{\text{Track capacity, } N_t}$

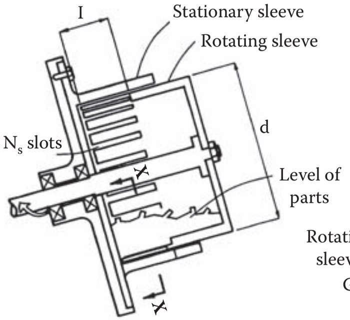
N_t = Track capacity = Maximum number of parts that can fit in track

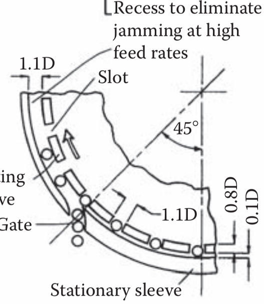
n = Frequency of blade reciprocation

EXTERNAL GATE HOPPER FEEDER

PART CODE	2	0	0

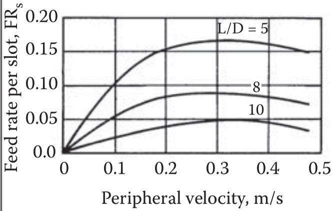






Enlarged section on X-X

$\frac{I}{D} = 11;\ \frac{d}{D} = 30;\ N_s = \frac{0.8d}{D} = 24$



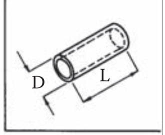
Feed rate = $FR_s \times N_s$

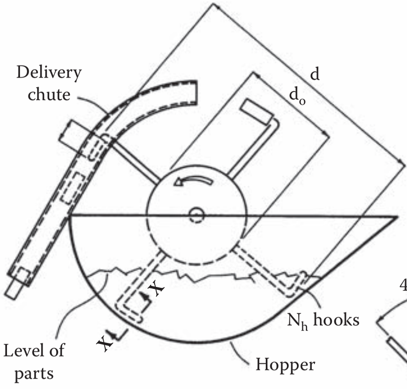
where:

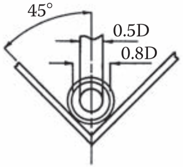
FR_s = Feed rate per slot

N_s = Number of slots in inner rotating sleeve

ROTARY HOOK HOPPER FEEDER	PART CODE	2	0	0

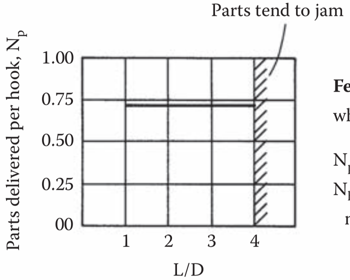






Enlarged section on X-X

$\frac{l}{D} = 2.5; \quad \frac{d}{D} = 26; \quad \frac{d}{d_o} = 2.6$



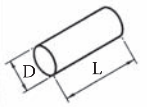
Feed rate = $N_p \times N_h \times n$

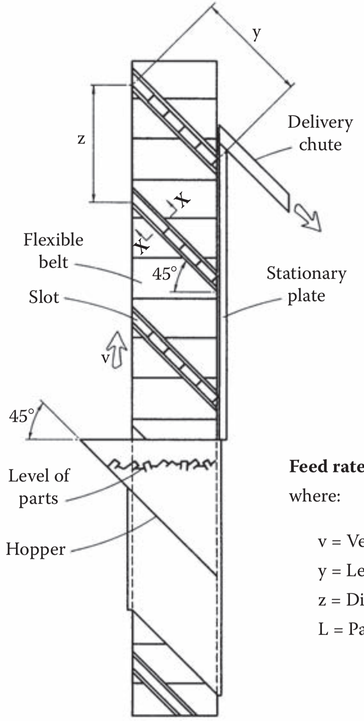
where:

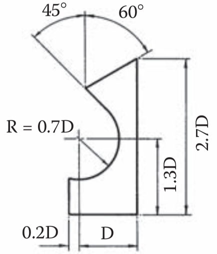
N_p = Parts delivered per hook
N_h = Number of hooks
n = Rotational frequency

ELEVATOR HOPPER FEEDER	PART CODE	2	0	0

$\frac{L}{D} > 2 \quad \frac{y}{L} > 4$







Enlarged section on X-X

Feed rate = $\frac{0.6 \times y \times v}{z \times L}$

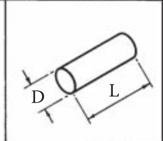
where:

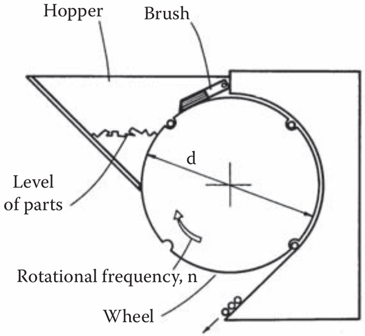
v = Velocity of the belt
y = Length of one slot
z = Distance between two slots
L = Part length

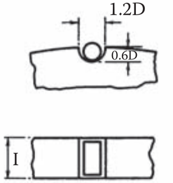
SLOTTED WHEEL HOPPER FEEDER

PART CODE	2	0	1

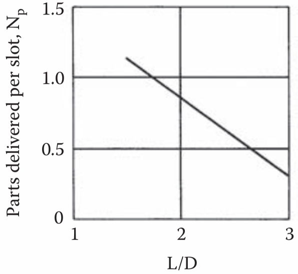
$\frac{d}{D} = 40 \quad \frac{I}{D} = 3.2$







Enlarged views of slot



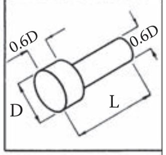
Feed rate = $N_p \times N_s \times n$
where:

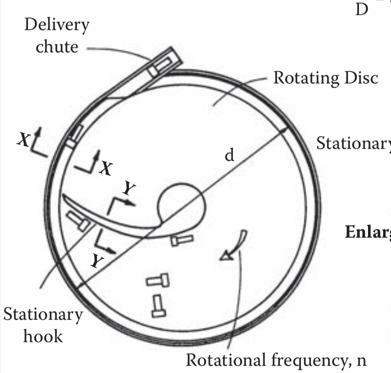
N_p = Parts delivered per slot
N_s = Number of slots
n = Rotational frequency

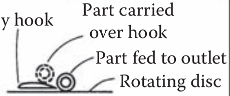
STATIONARY HOOK HOPPER FEEDER

PART CODE	2	1	0

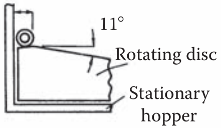
$\frac{d}{D} = 36$



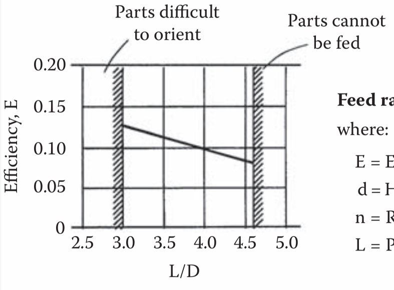




Enlarged section on Y-Y



Enlarged section on X-X



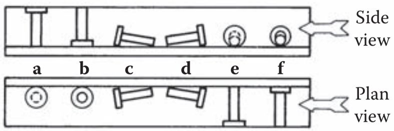
$0.1 < n < 0.3\ s^{-1}$

Feed rate = $\frac{E \times \pi \times d \times n}{L}$
where:

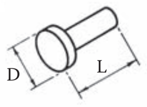
E = Efficiency
d = Hopper diameter
n = Rotational frequency of disc
L = Part length

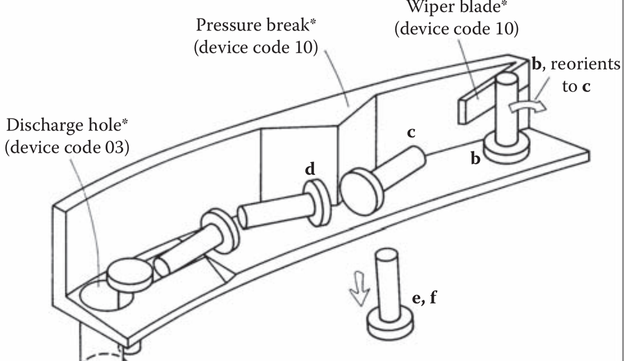
VIBRATORY BOWL FEEDER

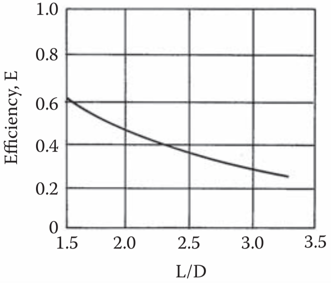
PART CODE 2 1 0



Part orientations







Feed rate = $\frac{v}{D} \times E$

where:

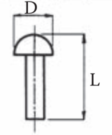
v = Conveying velocity

E = Efficiency

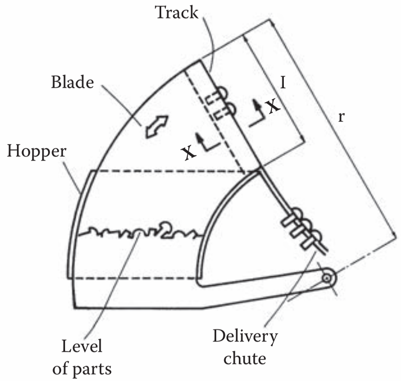
*For devices see section D3

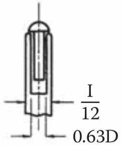
CENTERBOARD HOPPER FEEDER

PART CODE 2 1 1

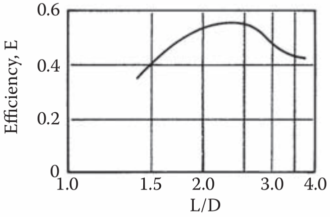


$\frac{I}{D} \sim 15$ $\frac{I}{r} = 0.5$





Enlarged section on X-X



Feed rate = $E \times N_t \times n$

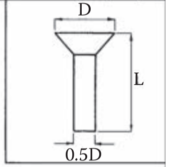
E = Efficiency = $\frac{\text{Number of parts fed per reciprocation}}{\text{Track capacity, } N_t}$

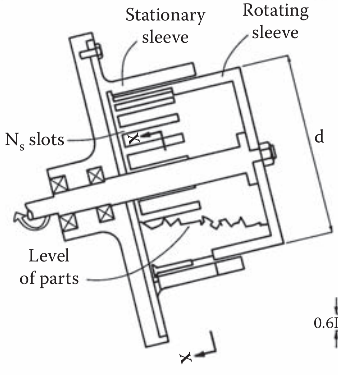
N_t = Track capacity = Maximum number of parts that can fit in track

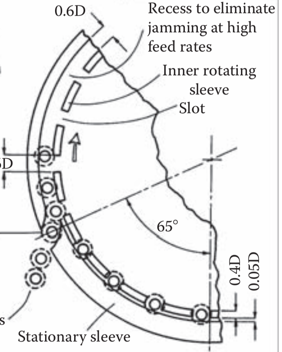
n = Frequency of blade reciprocation

EXTERNAL GATE HOPPER FEEDER

PART CODE	2	1	1

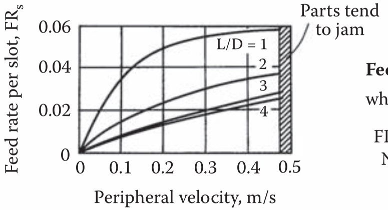






$\frac{d}{D} = 6 \quad \frac{I}{D} = 16 \quad N_s = \frac{1.5d}{D}$

Enlarged section on X-X



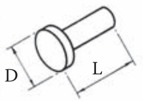
Feed rate = $FR_s \times N_s$

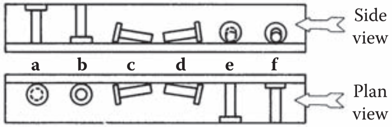
where:

FR_s = Feed rate per slot
N_s = Number of slots in inner rotating sleeve

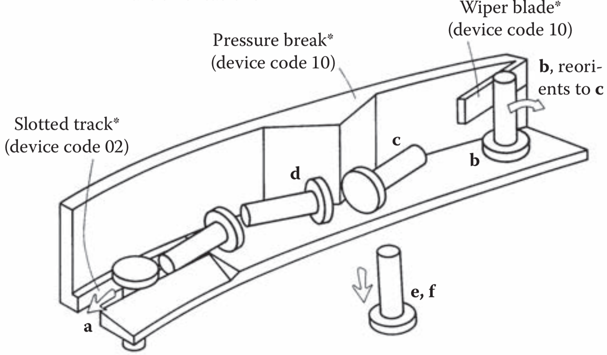
VIBRATORY BOWL FEEDER

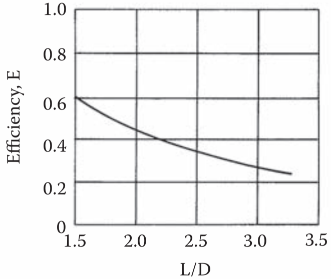
PART CODE	2	1	1





Part orientations

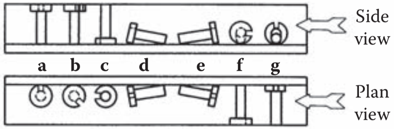

Wiper blade* (device code 10)
b, reori- ents to c
Pressure break* (device code 10)
Slotted track* (device code 02)
a
b
c
d
e, f



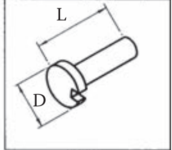
Where:
v = Conveying velocity
E = Efficiency

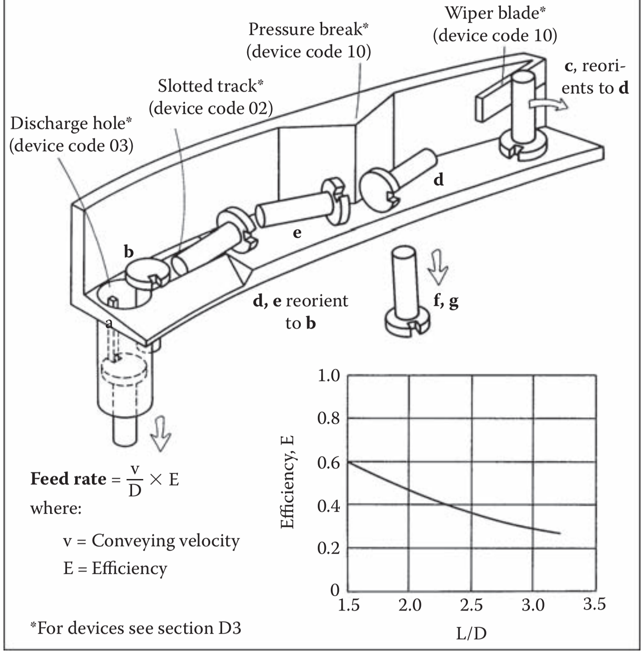
*For devices see section D3

VIBRATORY BOWL FEEDER	**PART CODE**	**2**	**1**	**5**



Part orientations





Feed rate = $\frac{v}{D} \times E$

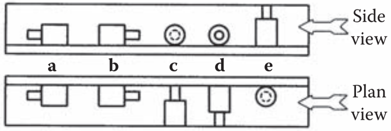
where:

v = Conveying velocity

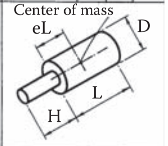
E = Efficiency

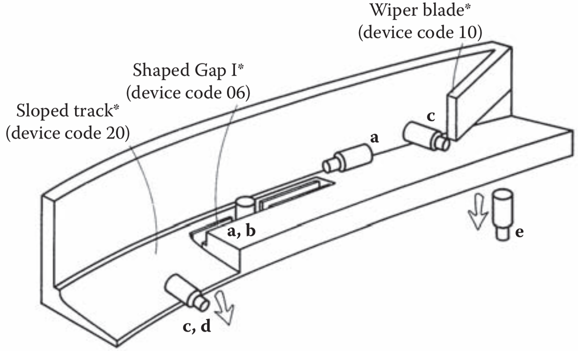
*For devices see section D3

VIBRATORY BOWL FEEDER	**PART CODE**	**2**	**2**	**0**



Part orientations



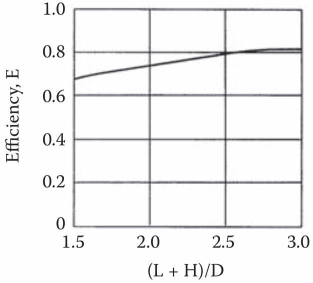


Feed rate = $\frac{v}{(L + H)} \times E$

where:

v = Conveying velocity

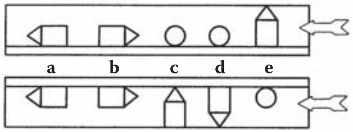
E = Efficiency

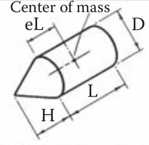


*For devices see section D3

VIBRATORY BOWL FEEDER

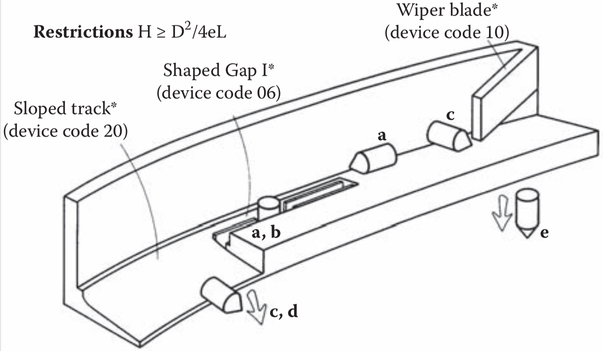
PART CODE 2 2 0





Part orientations

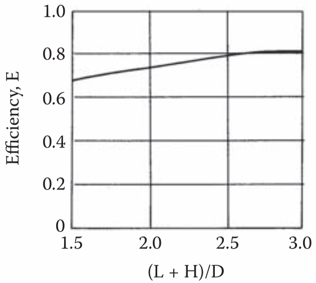
Restrictions $H \geq D^2/4eL$



Feed rate = $\frac{v}{(L + H)} \times E$

where:

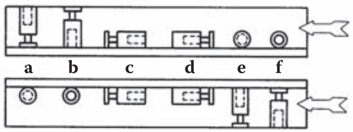
v = Conveying velocity
E = Efficiency

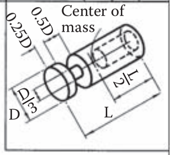


*For devices see section D3

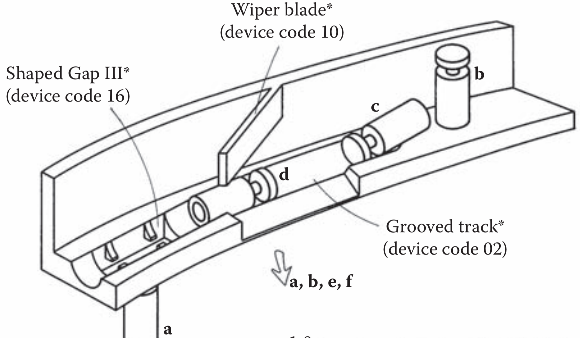
VIBRATORY BOWL FEEDER

PART CODE 2 3 0





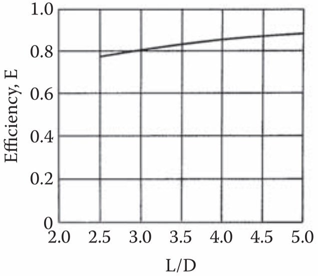
Part orientations



Feed rate = $\frac{v}{D} \times E \times P$

where:

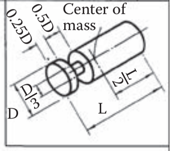
v = Conveying velocity
E = Efficiency
P = Probability that orientations c and d will fall through the shaped gap (see section D3 device code 16)

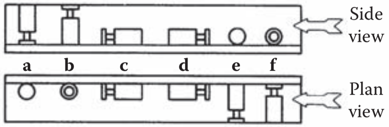


*For devices see section D3

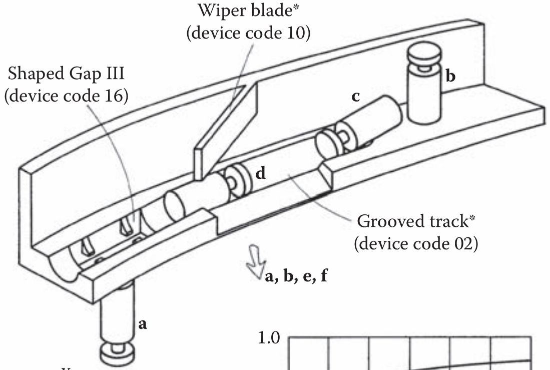
VIBRATORY BOWL FEEDER

PART CODE 2 4 0





Part orientations


Wiper blade* (device code 10)
Shaped Gap III (device code 16)
b
c
d
Grooved track* (device code 02)
a, b, e, f
a

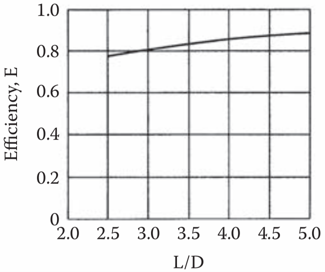
Feed rate = $\frac{v}{D} \times E \times P$

where:

v = Conveying velocity

E = Efficiency

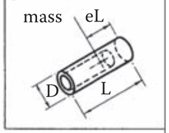
P = Probability that orientations c and d will fall through the shaped gap (see section D3 device code 16)

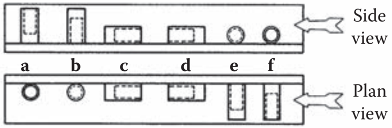


*For devices see section D3

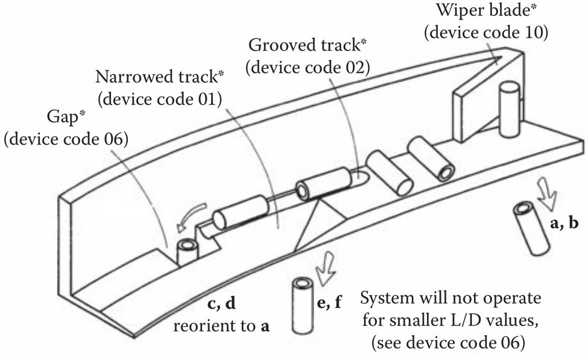
VIBRATORY BOWL FEEDER

PART CODE 2 5 0





Part orientations

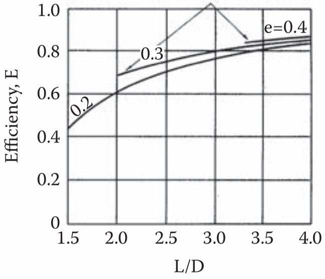

Wiper blade* (device code 10)
Grooved track* (device code 02)
Narrowed track* (device code 01)
Gap* (device code 06)
a, b
c, d reorient to a
e, f

Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

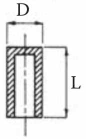
E = Efficiency

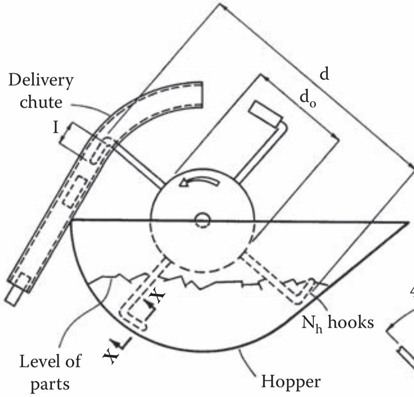


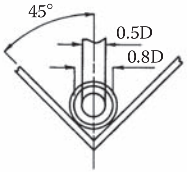
*For devices see section D3

ROTARY HOOK HOPPER FEEDER

PART CODE	2	5	0

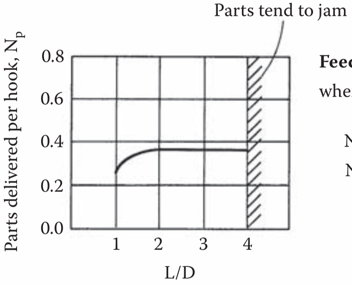






Enlarged section on X-X

$$\frac{I}{D} = 2.5; \quad \frac{d}{D} = 26; \quad \frac{I}{d_o} = 2.6$$



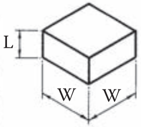
Feed rate = $N_p \times N_h \times n$

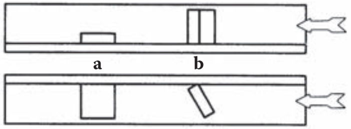
where:

N_p = Parts delivered per hook
N_h = Number of hooks
n = Rotational frequency

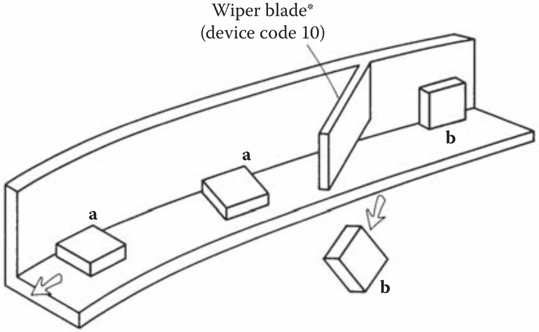
VIBRATORY BOWL FEEDER

PART CODE	3	0	0





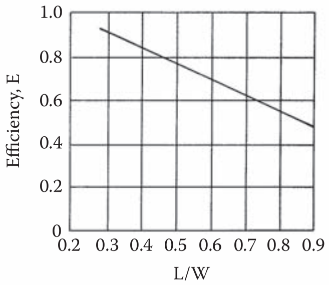
Part orientations



Feed rate = $\frac{v}{W} \times E$

where:

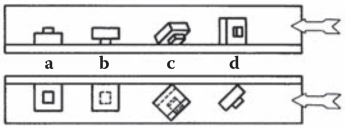
v = Conveying velocity
E = Efficiency



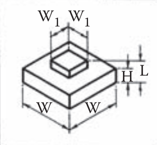
*For devices see section D3

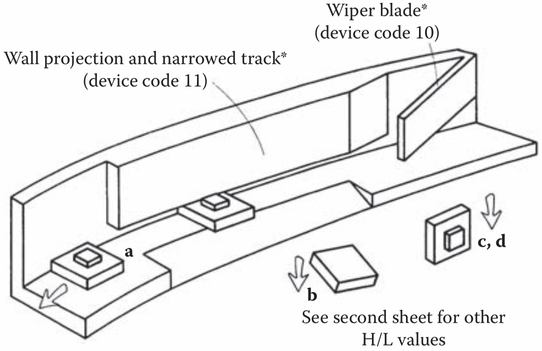
VIBRATORY BOWL FEEDER

PART CODE 3 0 4

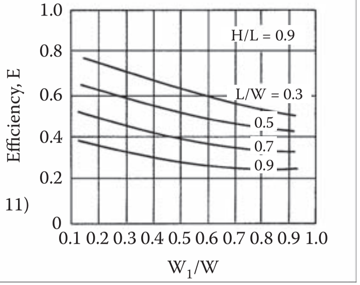


Part orientations





See second sheet for other H/L values



Feed rate = $\frac{v}{W} \times E \times P$

where:

v = Conveying velocity

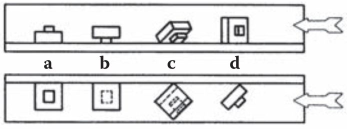
E = Efficiency

P = Probability that orientation **a** will pass the wall projection device (See section D3 device code 11)

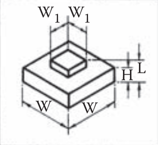
*For devices see section D3

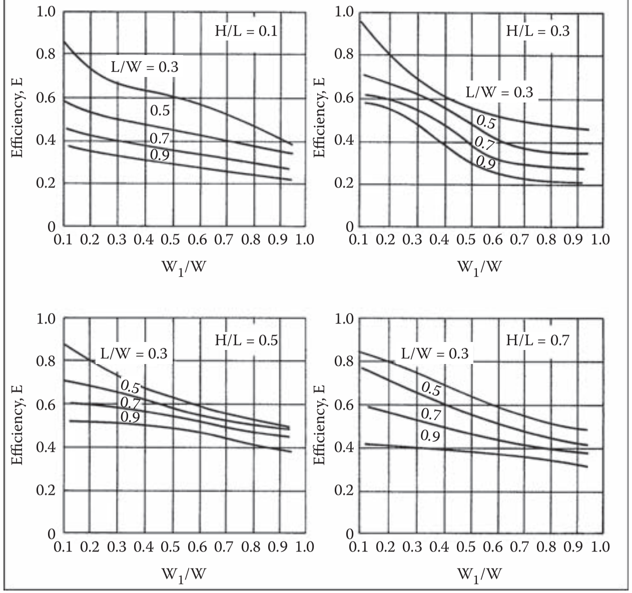
VIBRATORY BOWL FEEDER (Continued)

PART CODE 3 0 4



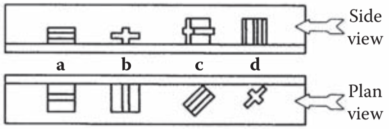
Part orientations



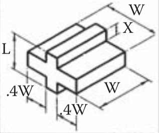


VIBRATORY BOWL FEEDER

PART CODE	3	1	0



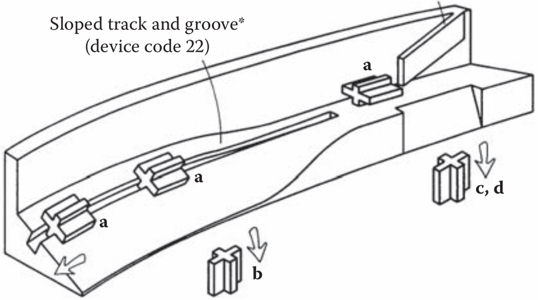
Part orientations



0.5 mm < X < 0.3W

Wiper blade* (device code 10)

Sloped track and groove* (device code 22)

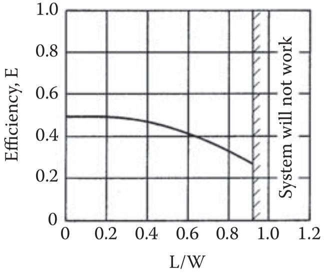


Feed rate = $\frac{v}{W} \times E$

where:

v = Conveying velocity

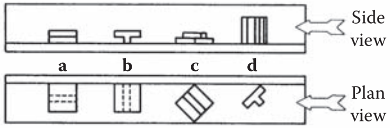
E = Efficiency



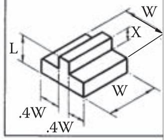
*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE	3	1	4



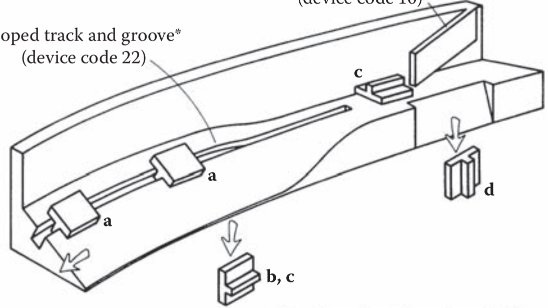
Part orientations



0.5 mm < X < 0.3W

Wiper blade* (device code 10)

Sloped track and groove* (device code 22)

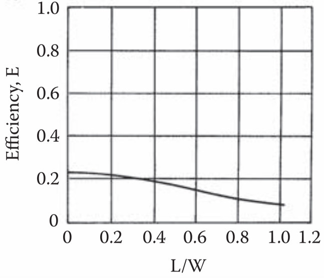


Feed rate = $\frac{v}{W} \times E$

where:

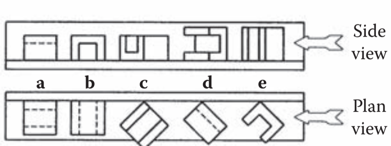
v = Conveying velocity

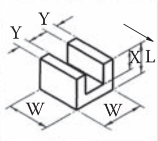
E = Efficiency



*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	3	2	6

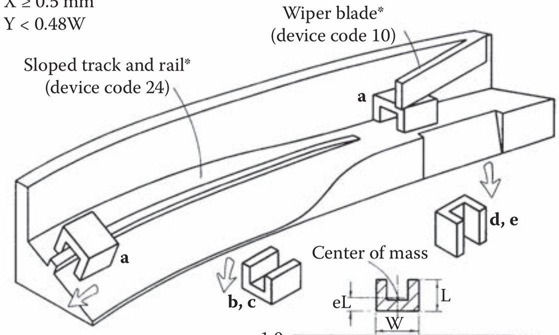




Part orientations

Note: Wiper blade (device code 10) not required with L/W > 0.9

X ≥ 0.5 mm
Y < 0.48W



Wiper blade* (device code 10)

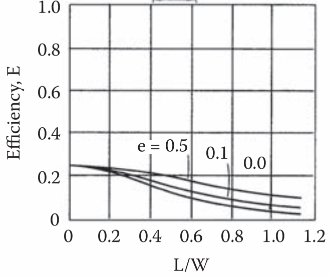
Sloped track and rail* (device code 24)

Center of mass

Feed rate = $\frac{v}{D} \times E$

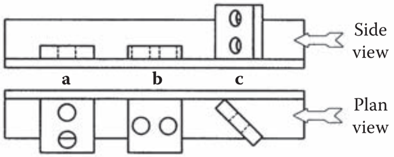
where:

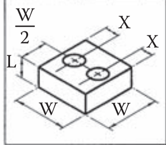
v = Conveying velocity
E = Efficiency



*For devices see section D3

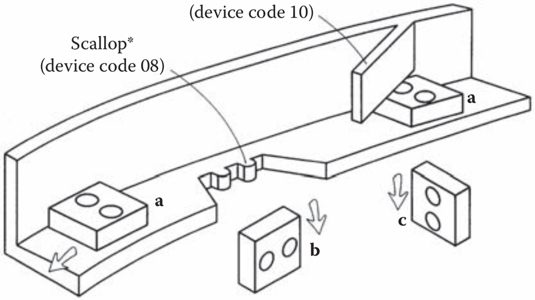
VIBRATORY BOWL FEEDER	PART CODE	3	3	1





Part orientations

X < 0.48W



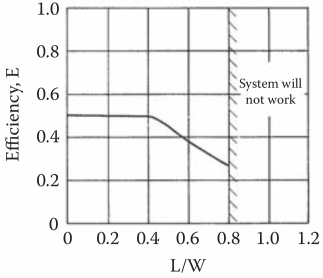
Wiper blade* (device code 10)

Scallop* (device code 08)

Feed rate = $\frac{v}{W} \times E$

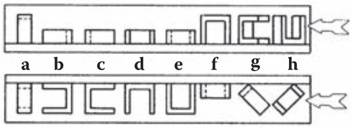
where:

v = Conveying velocity
E = Efficiency

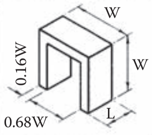


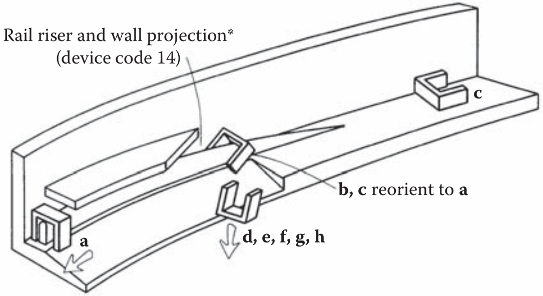
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	3	7	1



Part orientations



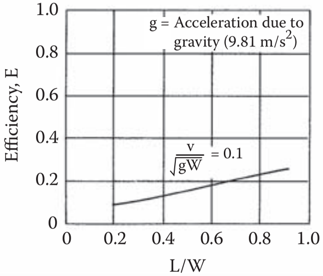


Feed rate = $\frac{v}{L} \times E$

where:

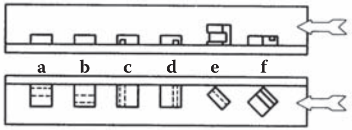
v = Conveying velocity

E = Efficiency

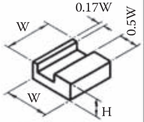


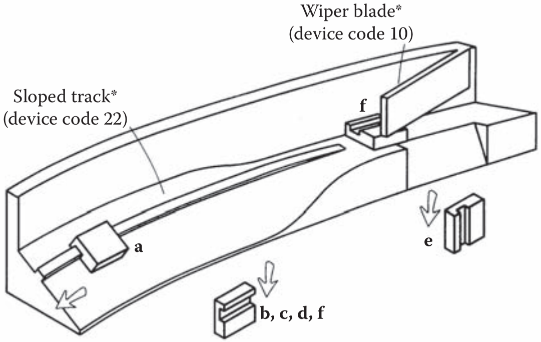
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	3	7	6



Part orientations



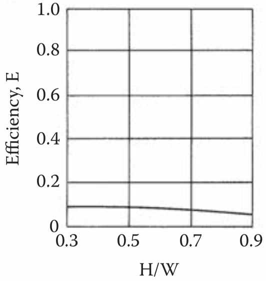


Feed rate = $\frac{v}{W} \times E$

where:

v = Conveying velocity

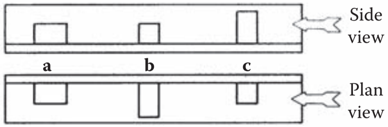
E = Efficiency



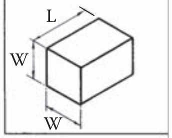
*For devices see section D3

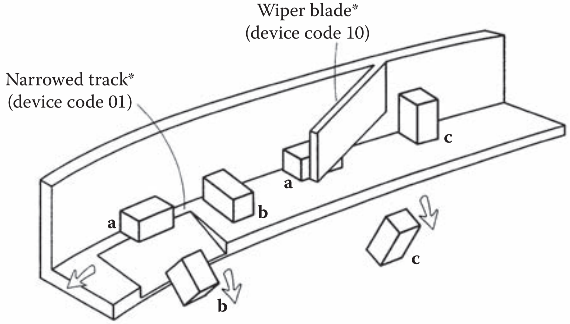
VIBRATORY BOWL FEEDER

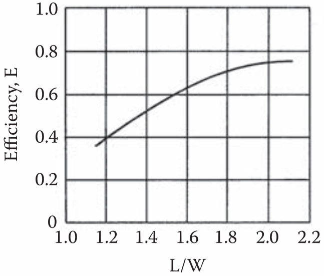
PART CODE	4	0	0



Part orientations







Feed rate = $\frac{v}{L} \times E$

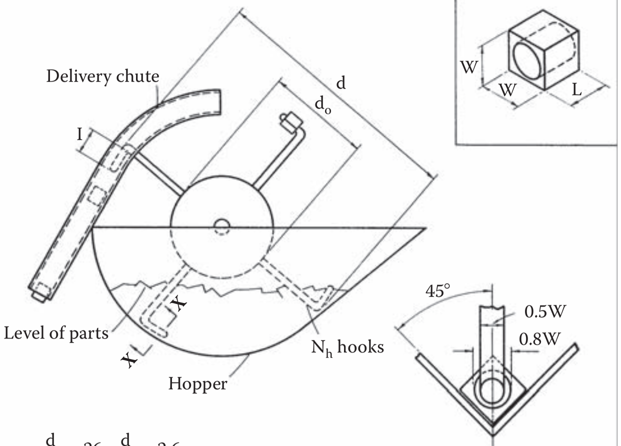
where:

v = Conveying velocity
E = Efficiency
L = Part length

*For devices see section D3

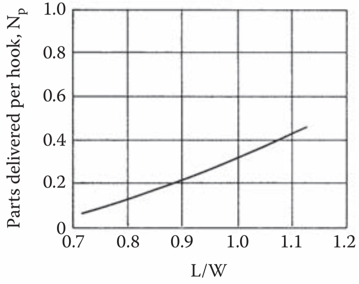
ROTARY HOOK HOPPER FEEDER

PART CODE	4	0	1



Section on X-X

$\frac{d}{W} = 26 \quad \frac{d}{d_o} = 2.6$

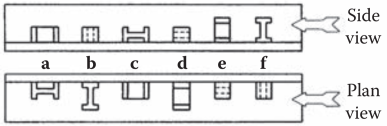


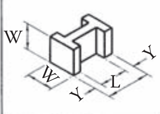
Feed rate = $N_p \times N_h \times n$

where:

N_p = Parts delivered per hook
N_h = Number of hooks
n = Rotational frequency

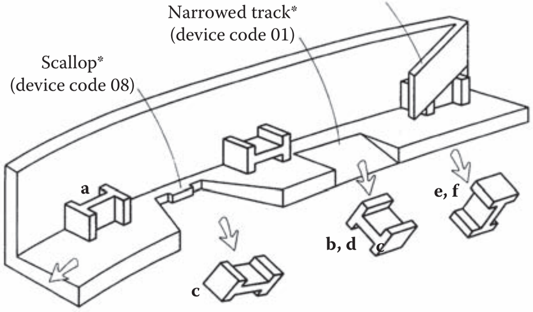
VIBRATORY BOWL FEEDER | **PART CODE** | **4** | **2** | **0**





Part orientations

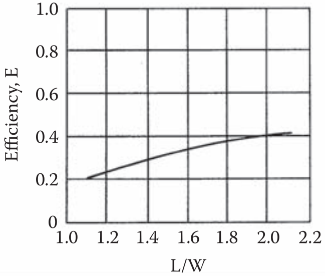
Y < 0.48L



$$\textbf{Feed rate} = \frac{v}{L} \times E$$

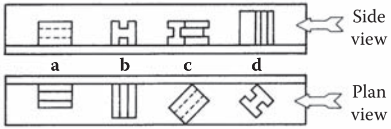
where:

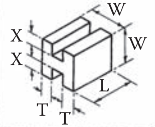
v = Conveying velocity
E = Efficiency



*For devices see section D3

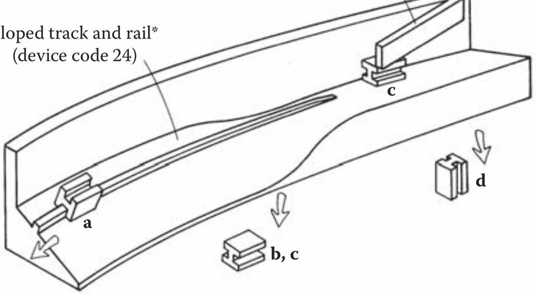
VIBRATORY BOWL FEEDER | **PART CODE** | **4** | **2** | **1**





Part orientations

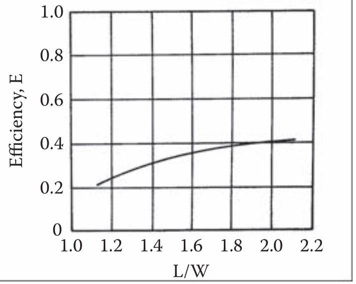
X ≥ 0.5 mm
T < 0.48W



$$\textbf{Feed rate} = \frac{v}{L} \times E$$

where:

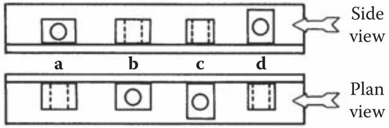
v = Conveying velocity
E = Efficiency

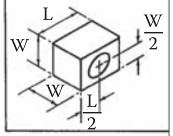


*For devices see section D3

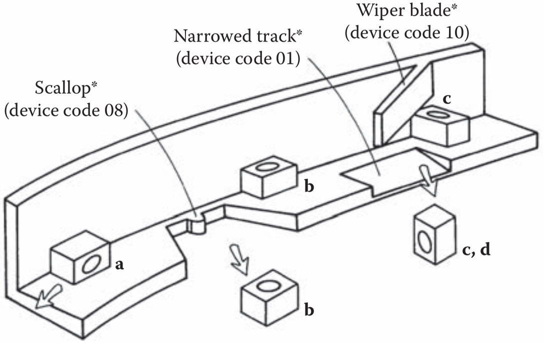
VIBRATORY BOWL FEEDER

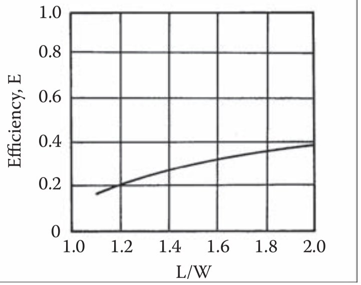
PART CODE	4	3	0





Part orientations





Feed rate = $\frac{v}{L} \times E$

where:

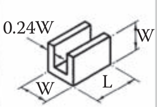
v = Conveying velocity
E = Efficiency

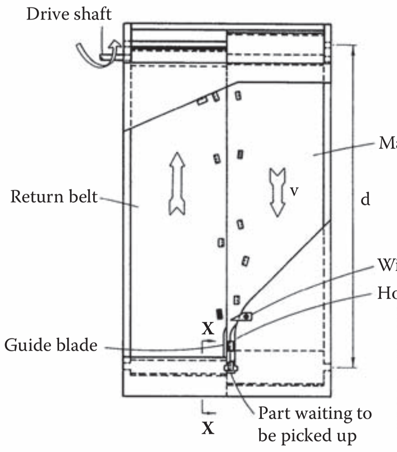
*For devices see section D3

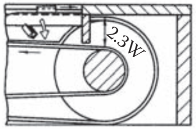
HORIZONTAL BELT FEEDER

PART CODE	4	7	1

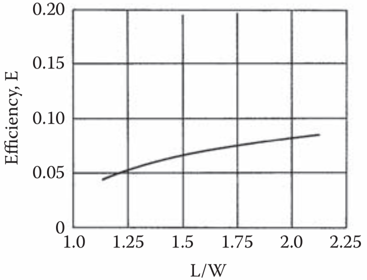
$\frac{d}{W} \approx 75$







Section on X-X



Feed rate = $\frac{v}{L} \times E$

where:

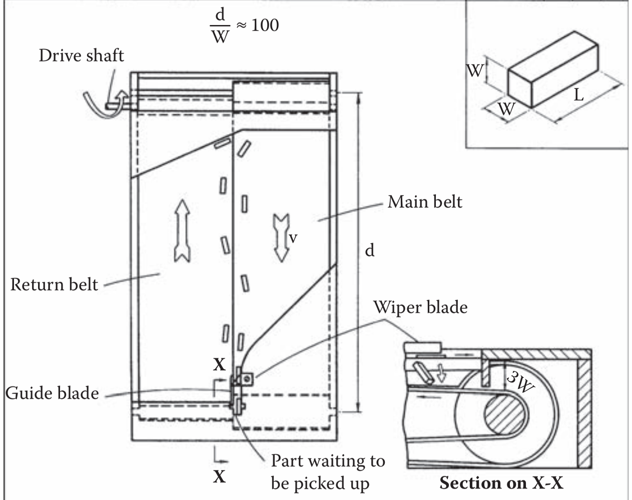
v = Main belt velocity
E = Efficiency
L = Part length

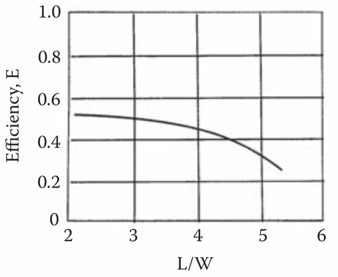
Load > 90 parts

HORIZONTAL BELT FEEDER

PART CODE	5	0	0

$\frac{d}{W} \approx 100$





Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity
E = Efficiency
L = Part length

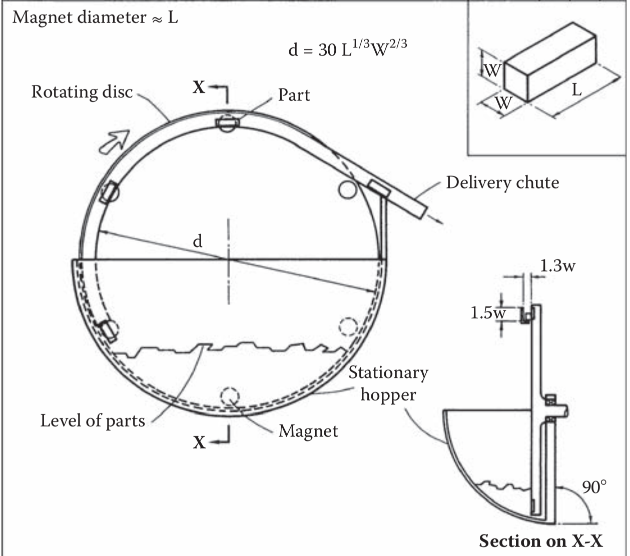
Load > 80 parts

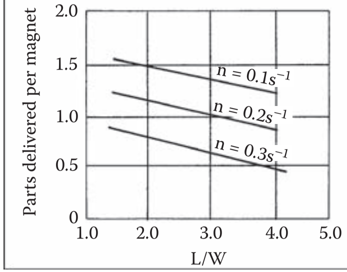
MAGNETIC DISC HOPPER FEEDER

PART CODE	5	0	0

Magnet diameter ≈ L

$d = 30\ L^{1/3}W^{2/3}$





Feed rate = $N_p \times N_m \times n$

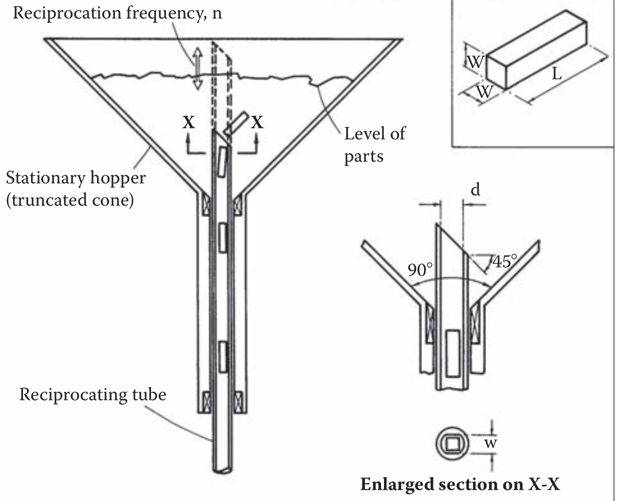
where:

N_p = Parts delivered per magnet
N_m = Number of magnets
n = Rotational frequency

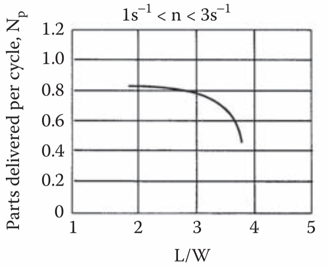
Magnet holding capacity is 10–20 times weight of one part.

RECIPROCATING TUBE HOPPER FEEDER

PART CODE	5	0	0


Reciprocation frequency, n
X
X
Level of parts
Stationary hopper (truncated cone)
Reciprocating tube
W
W
L
d
90°
45°
w

Enlarged section on X-X



d = 0.6 L

w = 1.4 W

Feed rate = $N_p \times n$

where:

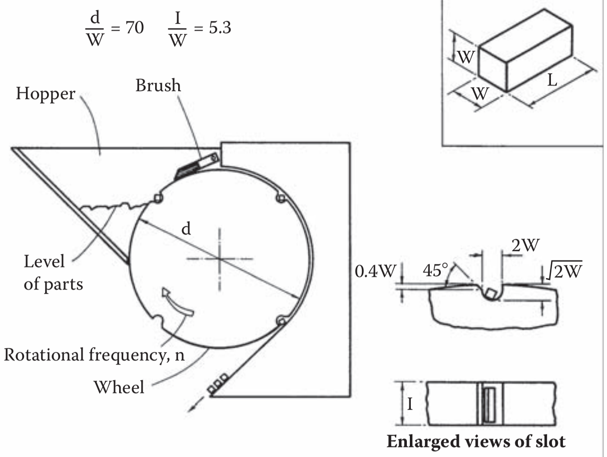
N_p = Parts delivered per cycle

n = Frequency of reciprocation

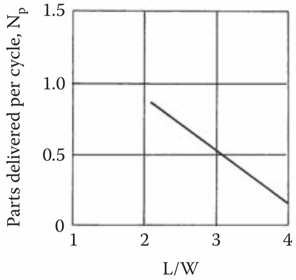
SLOTTED WHEEL HOPPER FEEDER

PART CODE	5	0	0

$$\frac{d}{W} = 70 \quad \frac{I}{W} = 5.3$$



Enlarged views of slot



Feed rate = $N_p \times N_s \times n$

where:

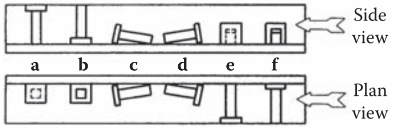
N_p = Parts delivered per slot

N_s = Number of slots

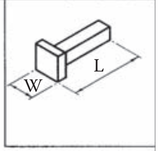
n = Rotational frequency

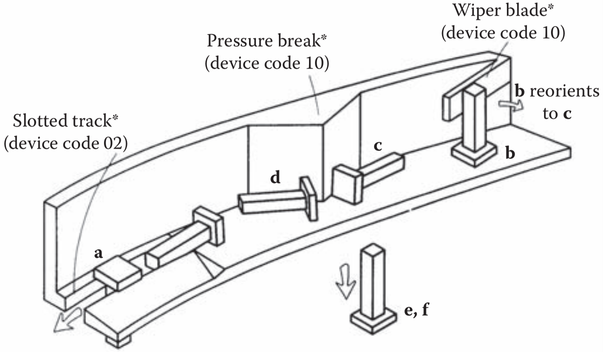
VIBRATORY BOWL FEEDER

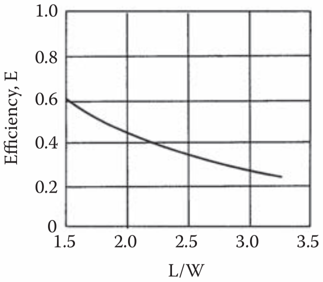
PART CODE	5	0	3



Part orientations







Feed rate = $\frac{v}{W} \times E$

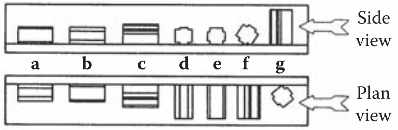
where:

v = Conveying velocity
E = Efficiency

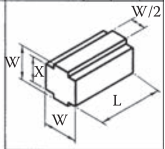
*For devices see section D3

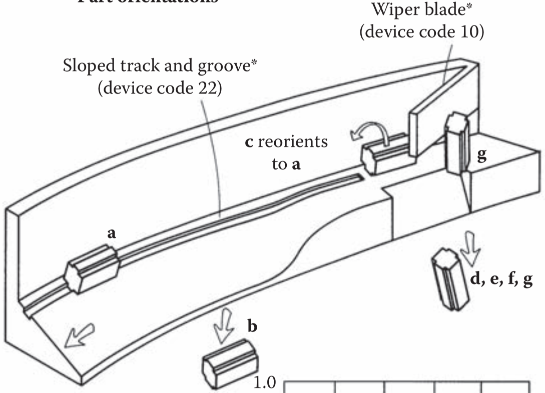
VIBRATORY BOWL FEEDER

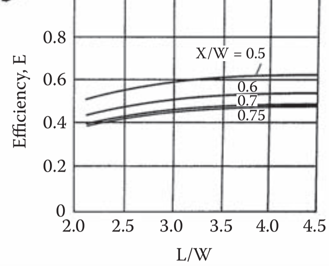
PART CODE	5	1	1



Part orientations







Feed rate = $\frac{v}{L} \times E$

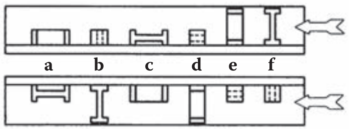
where:

v = Conveying velocity
E = Efficiency

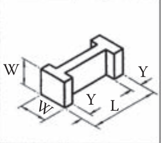
*For devices see section D3

VIBRATORY BOWL FEEDER

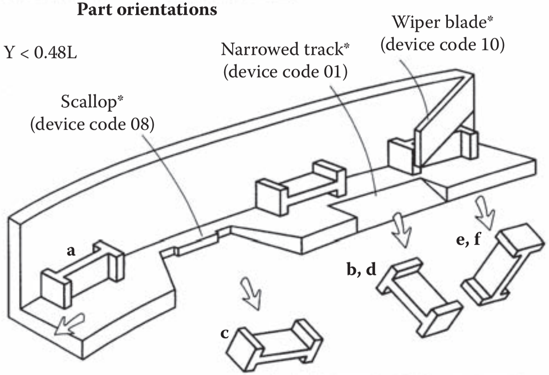
PART CODE	5	2	0



Part orientations



Y < 0.48L

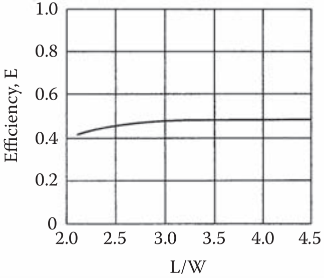


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

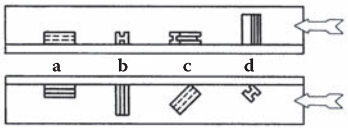
E = Efficiency



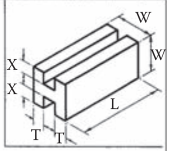
*For devices see section D3

VIBRATORY BOWL FEEDER

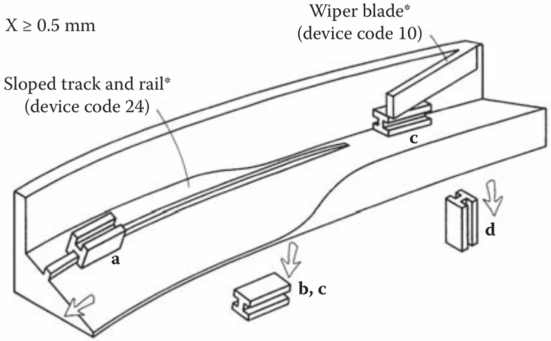
PART CODE	5	2	1



Part orientations



X ≥ 0.5 mm

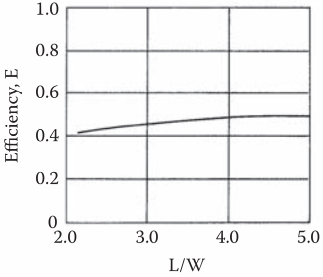


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

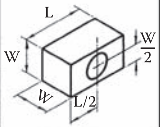
E = Efficiency

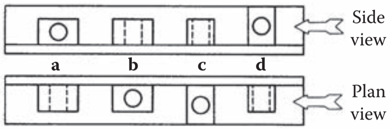


*For devices see section D3

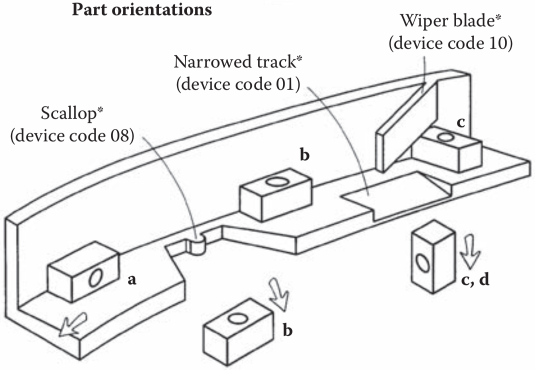
VIBRATORY BOWL FEEDER

PART CODE	5	3	0





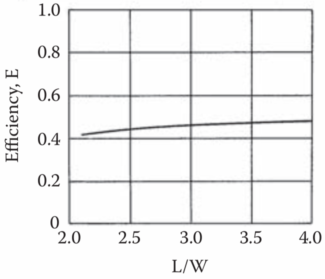
Part orientations



Feed rate $= \frac{v}{L} \times E$

where:

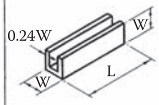
v = Conveying velocity
E = Efficiency



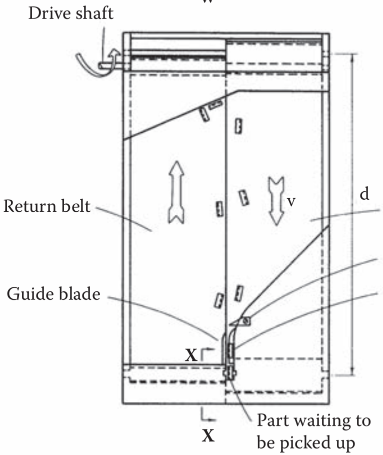
*For devices see section D3

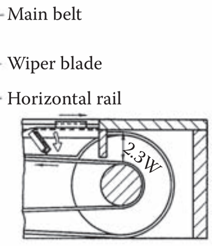
HORIZONTAL BELT FEEDER

PART CODE	5	7	1

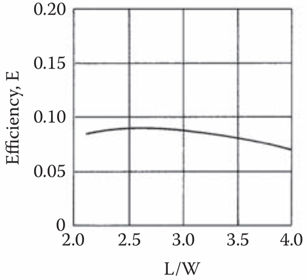


$\frac{d}{W} \approx 75$





Section on X-X



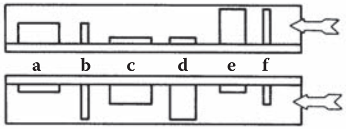
Feed rate $= \frac{v}{L} \times E$

where:

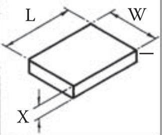
v = Main belt velocity
E = Efficiency
L = Part length

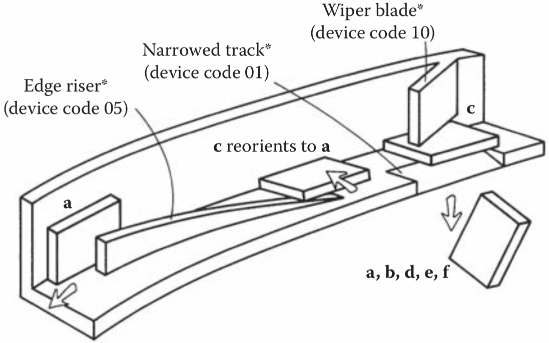
Load > 90 parts

VIBRATORY BOWL FEEDER	PART CODE	6	0	0



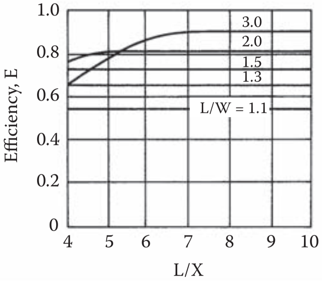
Part orientations





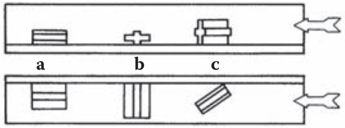
Feed rate = $\frac{v}{L} \times E$
where:

v = Conveying velocity
E = Efficiency

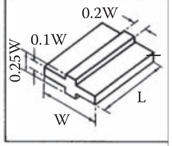


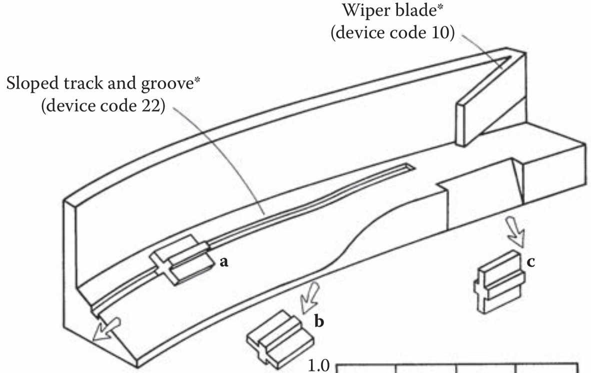
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	6	0	1



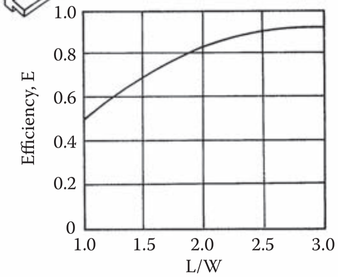
Part orientations





Feed rate = $\frac{v}{L} \times E$
where:

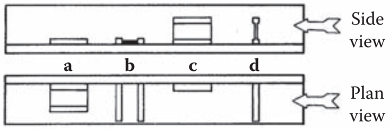
v = Conveying velocity
E = Efficiency



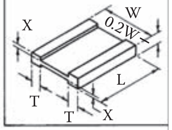
*For devices see section D3

VIBRATORY BOWL FEEDER

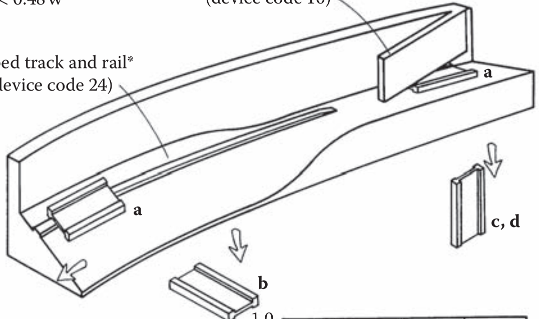
PART CODE 6 0 4



Part orientations

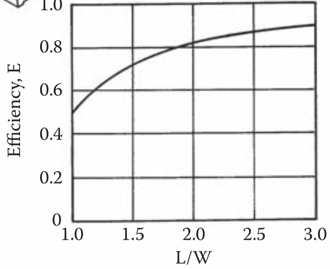


X ≥ 0.5 mm
T < 0.48W



Wiper blade*
(device code 10)

Sloped track and rail*
(device code 24)



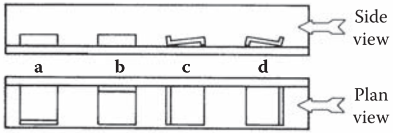
Feed rate = $\frac{v}{L} \times E$
where:

v = Conveying velocity
E = Efficiency

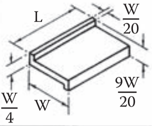
*For devices see section D3

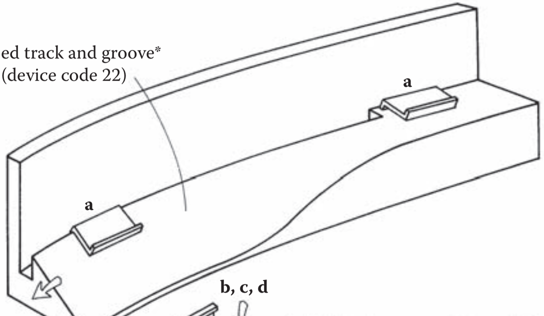
VIBRATORY BOWL FEEDER

PART CODE 6 1 0

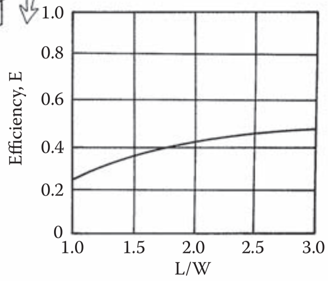


Part orientations





Sloped track and groove*
(device code 22)

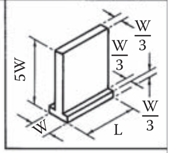


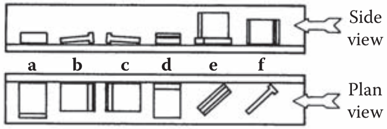
Feed rate = $\frac{v}{L} \times E$
where:

v = Conveying velocity
E = Efficiency

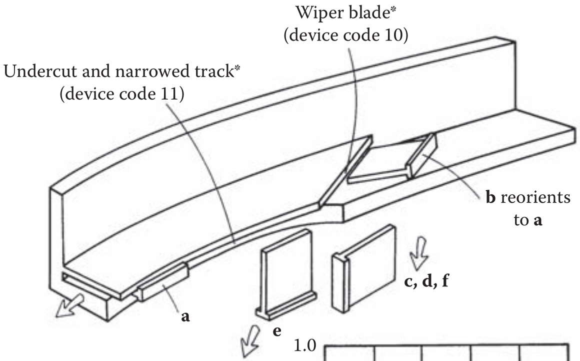
*For devices see section D3

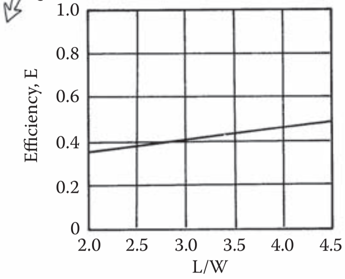
VIBRATORY BOWL FEEDER PART CODE 6 1 1





Part orientations





Feed rate = $\frac{v}{L} \times E$

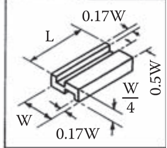
where:

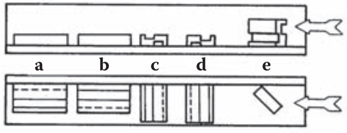
v = Conveying velocity

E = Efficiency

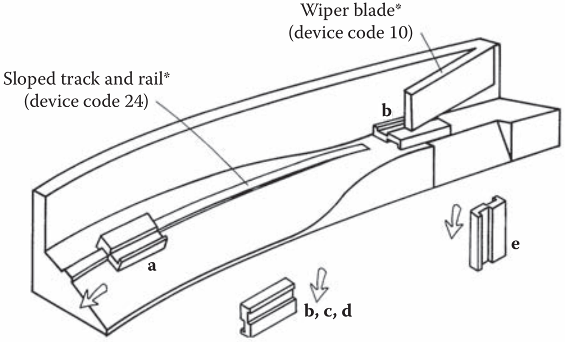
*For devices see section D3

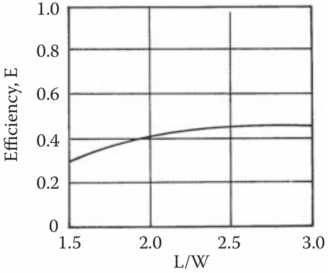
VIBRATORY BOWL FEEDER PART CODE 6 1 3





Part orientations





Feed rate = $\frac{v}{L} \times E$

where:

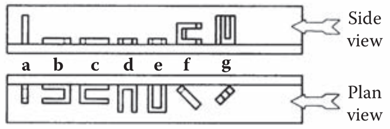
v = Conveying velocity

E = Efficiency

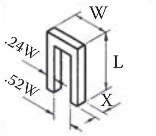
*For devices see section D3

VIBRATORY BOWL FEEDER

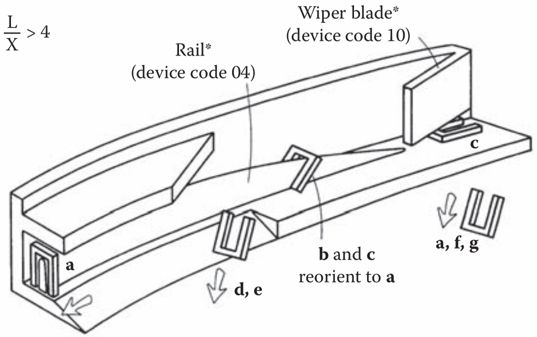
PART CODE	6	1	5



Part orientations



$\frac{L}{X} > 4$

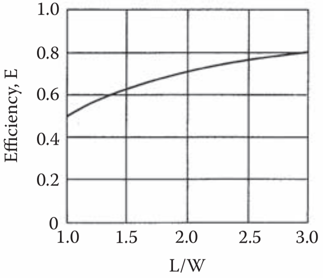


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

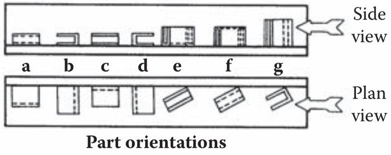
E = Efficiency



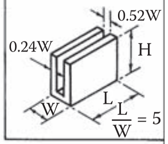
*For devices see section D3

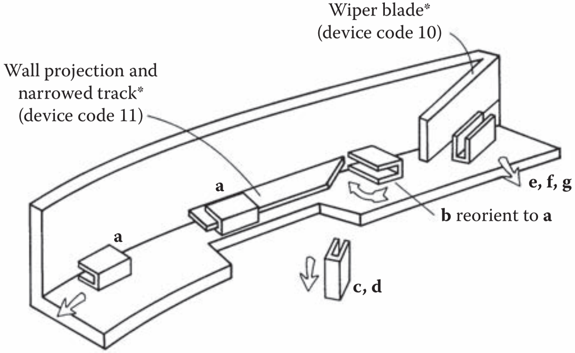
VIBRATORY BOWL FEEDER

PART CODE	6	2	3



Part orientations



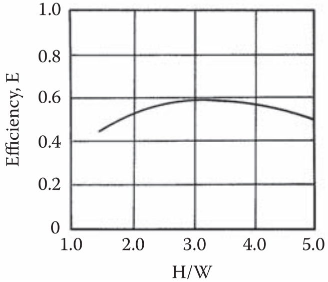


Feed rate = $\frac{v}{L} \times E$

where:

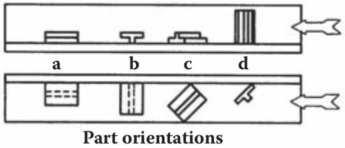
v = Conveying velocity

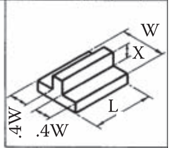
E = Efficiency

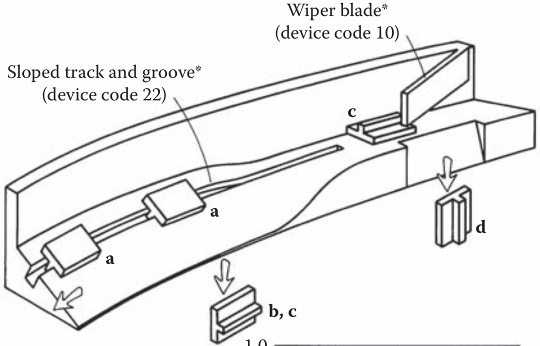


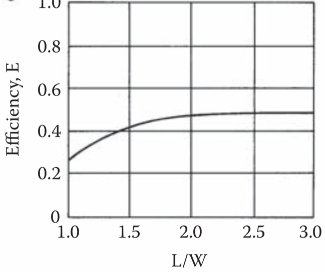
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	6	3	0









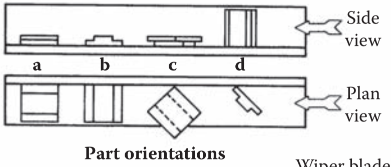
Feed rate = $\frac{v}{L} \times E$

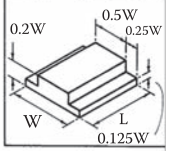
where:

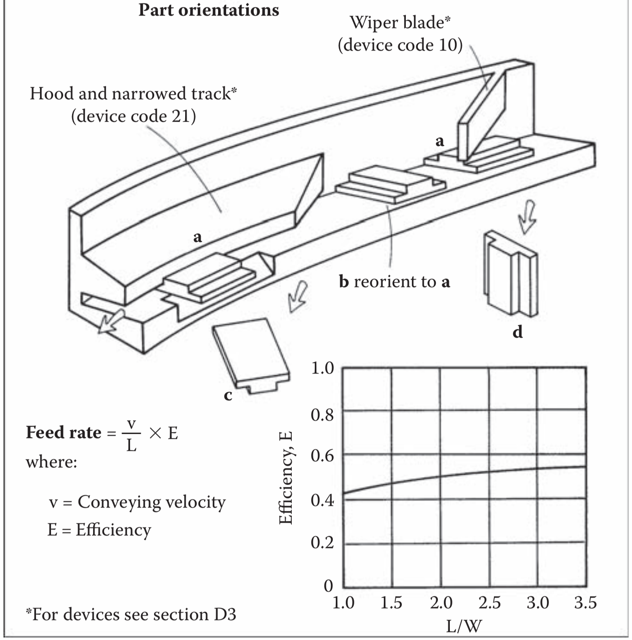
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	6	3	1







Feed rate = $\frac{v}{L} \times E$

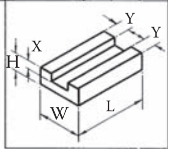
where:

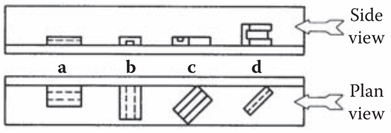
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

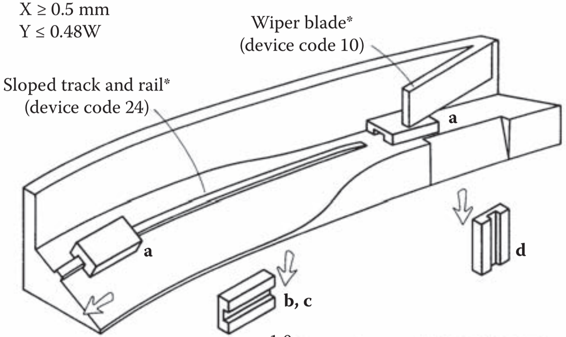
PART CODE	6	3	3

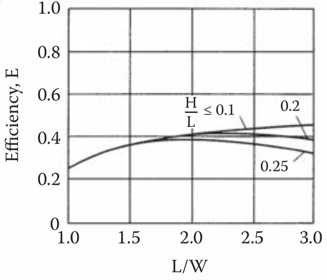




Part orientations

X ≥ 0.5 mm
Y ≤ 0.48W





Feed rate = $\frac{v}{L} \times E$

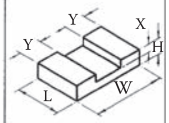
where:

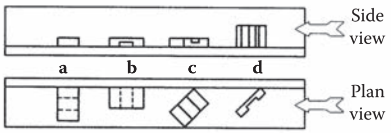
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

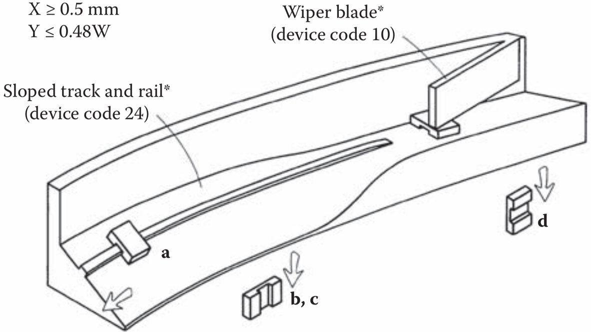
PART CODE	6	3	4

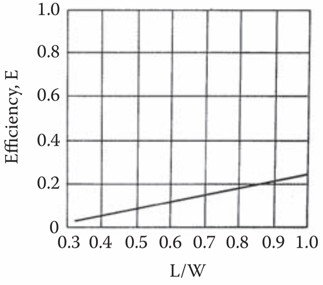




Part orientations

X ≥ 0.5 mm
Y ≤ 0.48W





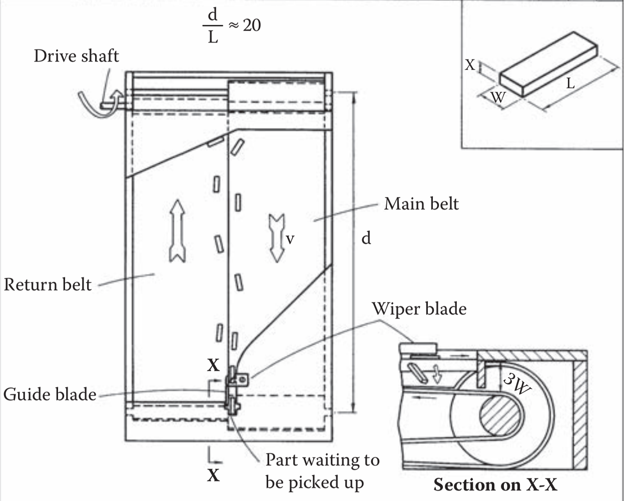
Feed rate = $\frac{v}{L} \times E$

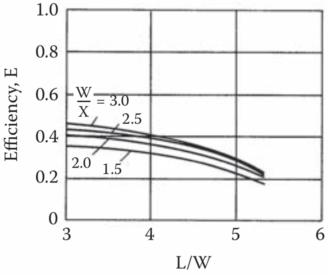
where:

v = Conveying velocity
E = Efficiency

*For devices see section D3

HORIZONTAL BELT FEEDER	PART CODE	7	0	0





Feed rate $= \frac{v}{L} \times E$

where:

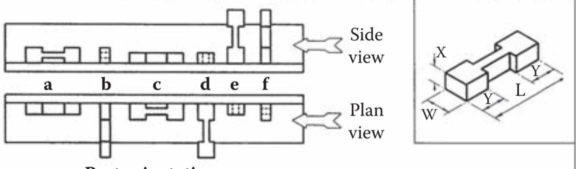
v = Main belt velocity

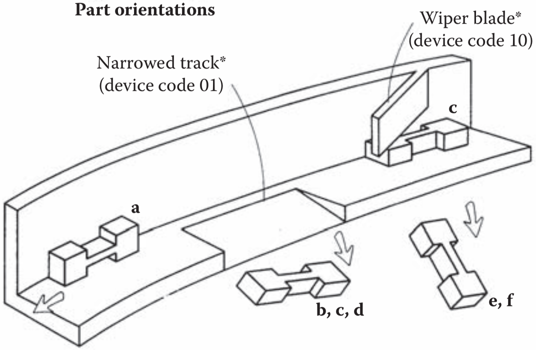
E = Efficiency

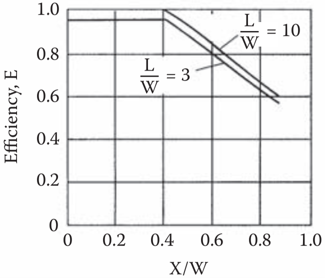
L = Part length

Load > 80 parts

VIBRATORY BOWL FEEDER	PART CODE	7	0	0




Wiper blade* (device code 10)
Narrowed track* (device code 01)
c
a
b, c, d
e, f



Feed rate $= \frac{v}{L} \times E$

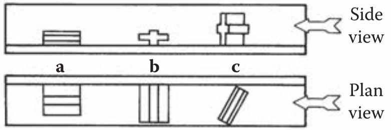
where:

v = Conveying velocity

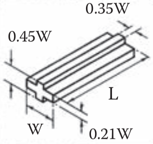
E = Efficiency

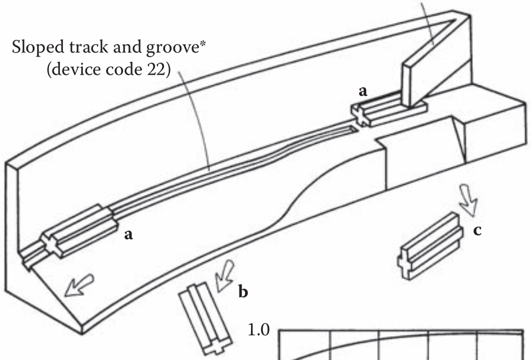
*For devices see section D3

VIBRATORY BOWL FEEDER	**PART CODE**	**7**	**0**	**1**



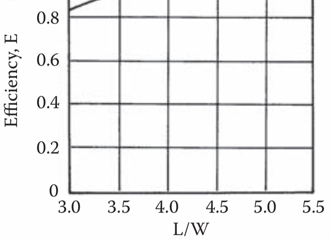
Part orientations





Wiper blade*
(device code 10)

Sloped track and groove*
(device code 22)



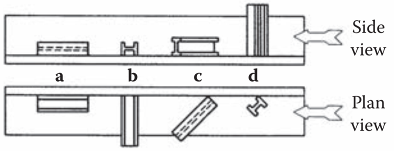
Feed rate = $\frac{v}{L} \times E$

where:

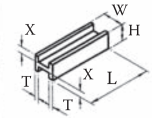
v = Conveying velocity
E = Efficiency

*For devices see section D3

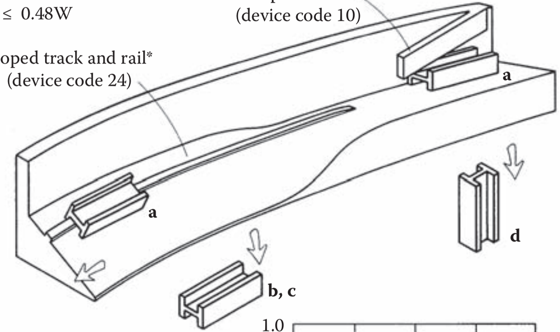
VIBRATORY BOWL FEEDER	**PART CODE**	**7**	**0**	**4**



Part orientations

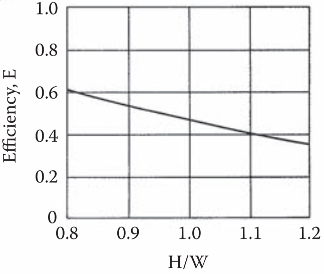


X ≥ 0.5 mm
T ≤ 0.48W



Wiper blade*
(device code 10)

Sloped track and rail*
(device code 24)

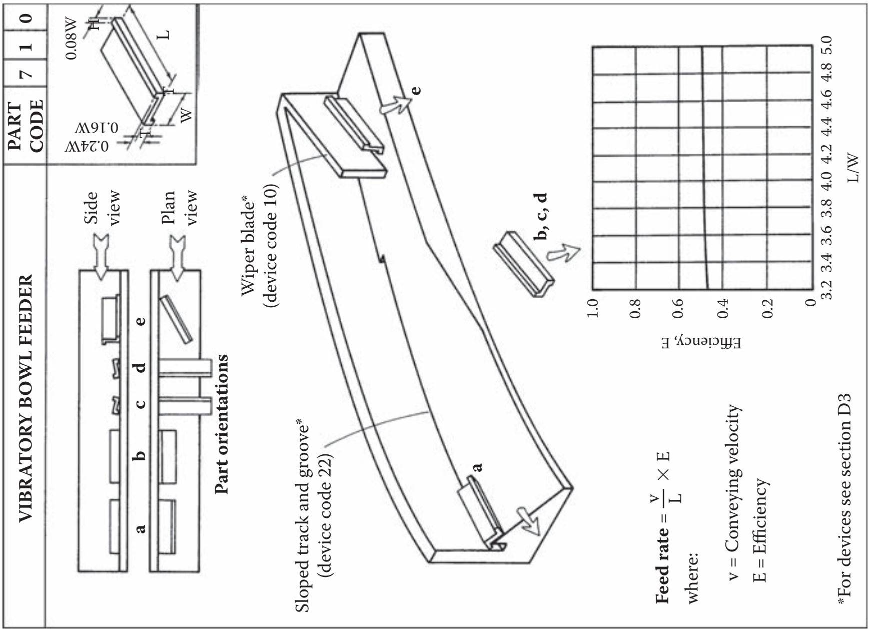


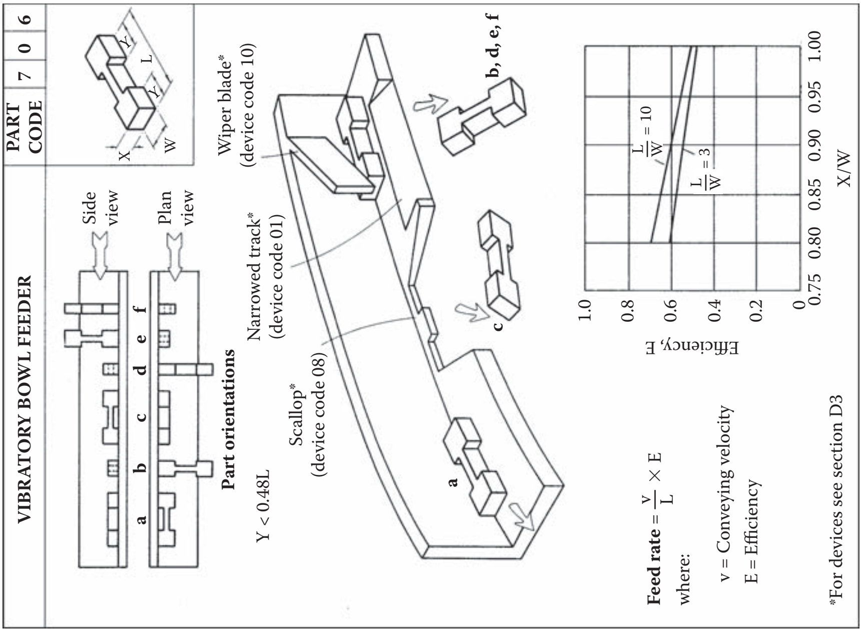
Feed rate = $\frac{v}{L} \times E$

where:

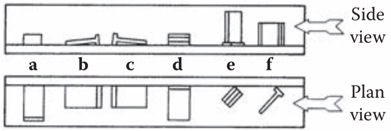
v = Conveying velocity
E = Efficiency

*For devices see section D3

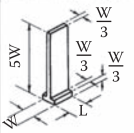

VIBRATORY BOWL FEEDER
PART CODE 7 1 0
0.08W
0.24W
0.16W
T
T
W
L
Side view
Plan view
a
b
c
d
e
Part orientations
Wiper blade* (device code 10)
Sloped track and groove* (device code 22)
a
e
b, c, d
Efficiency, E
1.0
0.8
0.6
0.4
0.2
0
3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0
L/W
Feed rate = $\frac{v}{L} \times E$
where:
v = Conveying velocity
E = Efficiency
*For devices see section D3

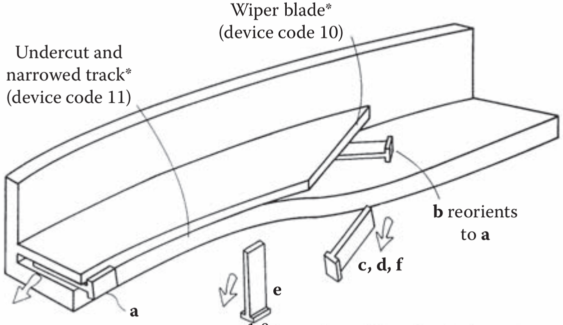

VIBRATORY BOWL FEEDER
PART CODE 7 0 6
X
W
Y
Y
L
Side view
Plan view
a
b
c
d
e
f
Part orientations
Y < 0.48L
Wiper blade* (device code 10)
Narrowed track* (device code 01)
Scallop* (device code 08)
a
c
b, d, e, f
$\frac{L}{W} = 10$
$\frac{L}{W} = 3$
Efficiency, E
1.0
0.8
0.6
0.4
0.2
0
0.75 0.80 0.85 0.90 0.95 1.00
X/W
Feed rate = $\frac{v}{L} \times E$
where:
v = Conveying velocity
E = Efficiency
*For devices see section D3

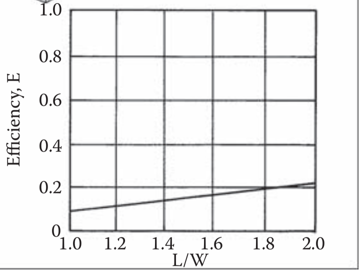
VIBRATORY BOWL FEEDER	PART CODE	7	1	1



Part orientations







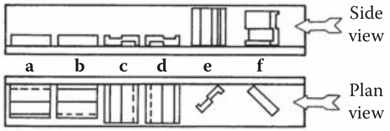
Feed rate = $\frac{v}{L} \times E$

where:

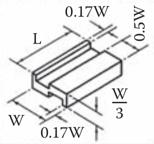
v = Conveying velocity
E = Efficiency

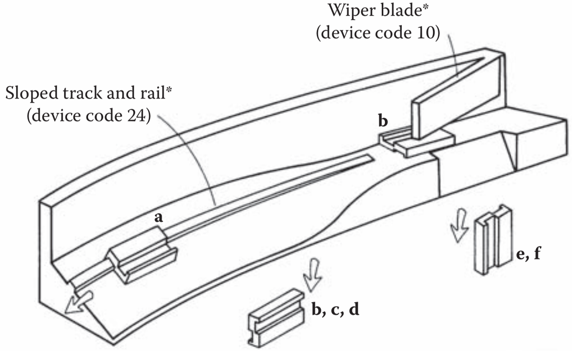
*For devices see section D3

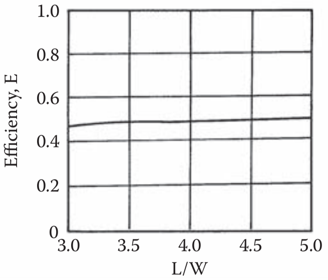
VIBRATORY BOWL FEEDER	PART CODE	7	1	3



Part orientations







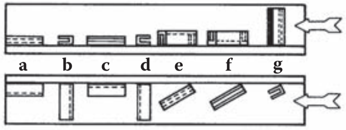
Feed rate = $\frac{v}{L} \times E$

where:

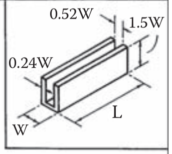
v = Conveying velocity
E = Efficiency

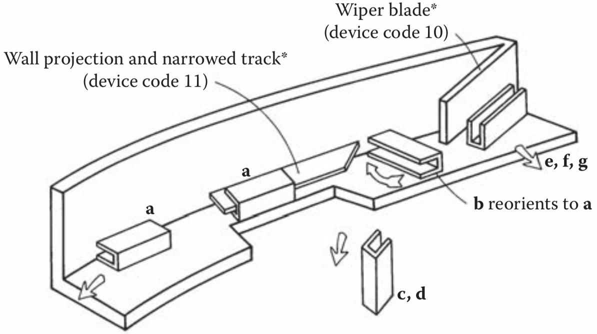
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	7	2	3



Part orientations



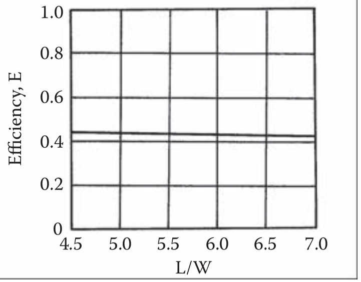


Feed rate = $\frac{v}{L} \times E$

where:

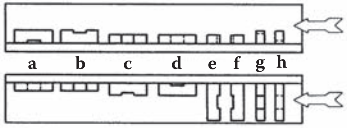
v = Conveying velocity

E = Efficiency

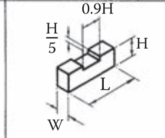


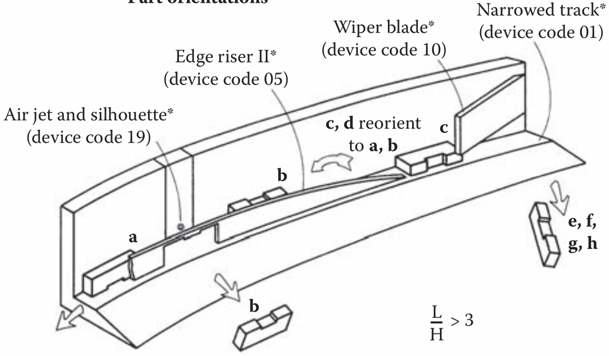
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	7	2	5



Part orientations





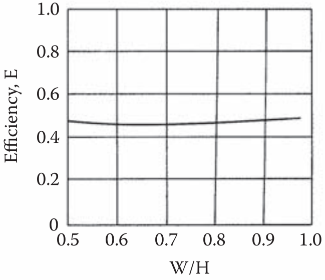
$\frac{L}{H} > 3$

Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

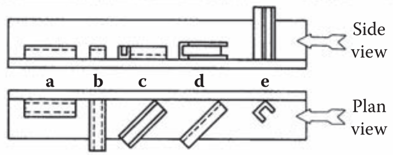
E = Efficiency



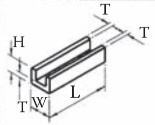
*For devices see section D3

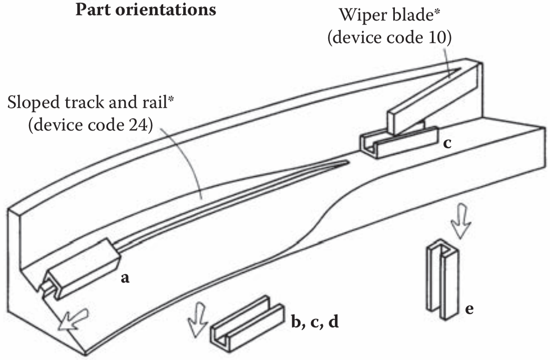
VIBRATORY BOWL FEEDER

PART CODE	7	3	3



Part orientations



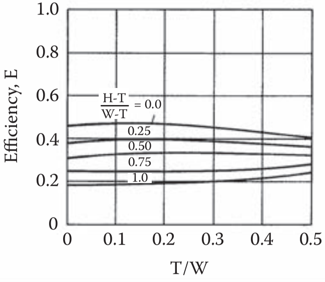


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

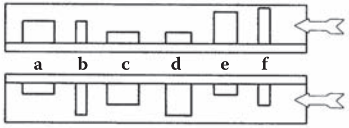
E = Efficiency



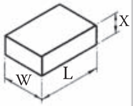
*For devices see section D3

VIBRATORY BOWL FEEDER

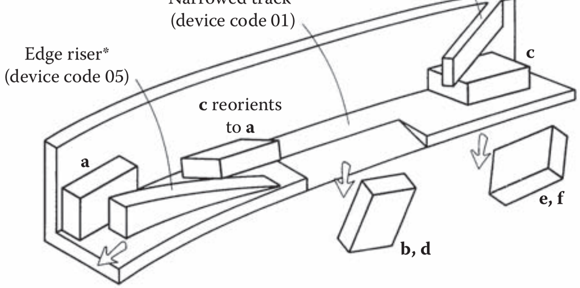
PART CODE	8	0	0



Part orientations



$1.1 < \frac{W}{X} < 1.9$

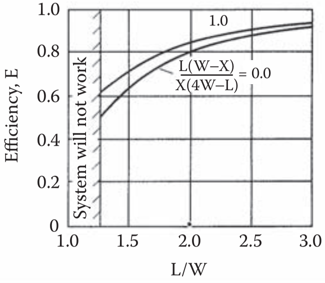


Feed rate = $\frac{v}{L} \times E$

where:

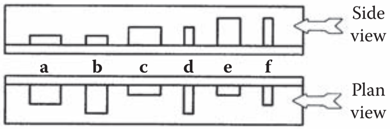
v = Conveying velocity

E = Efficiency

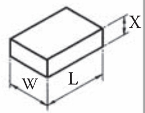


*For devices see section D3

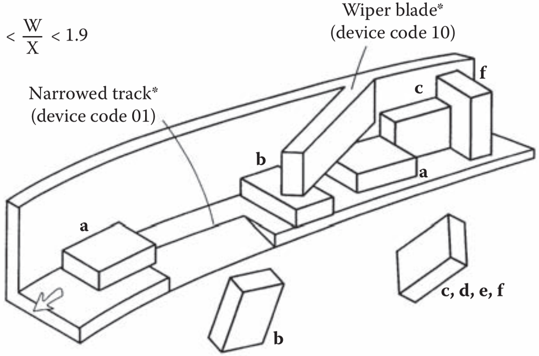
VIBRATORY BOWL FEEDER	DEVICE CODE	8	0	0



Part orientations



$1.1 < \frac{W}{X} < 1.9$

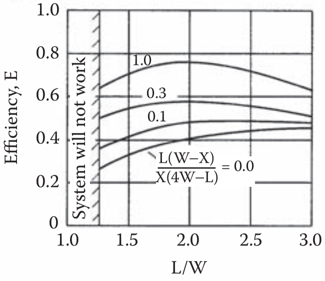


Feed rate = $\frac{v}{L} \times E$

where:

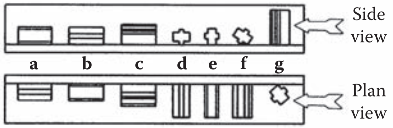
v = Conveying velocity

E = Efficiency

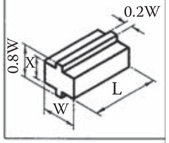


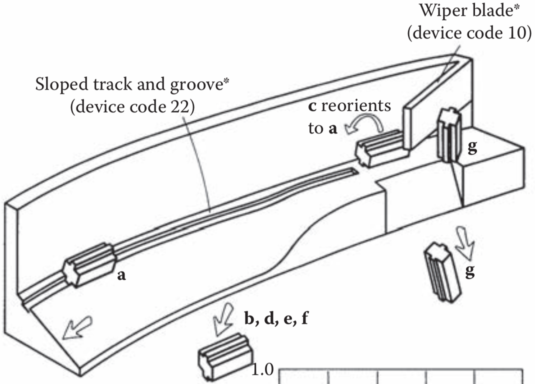
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	8	0	1



Part orientations



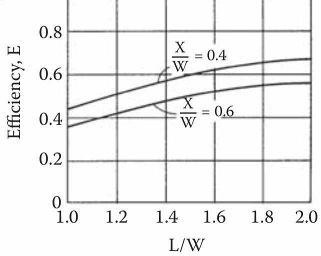


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

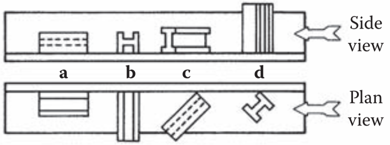
E = Efficiency



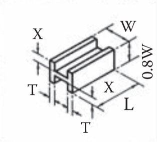
*For devices see section D3

VIBRATORY BOWL FEEDER

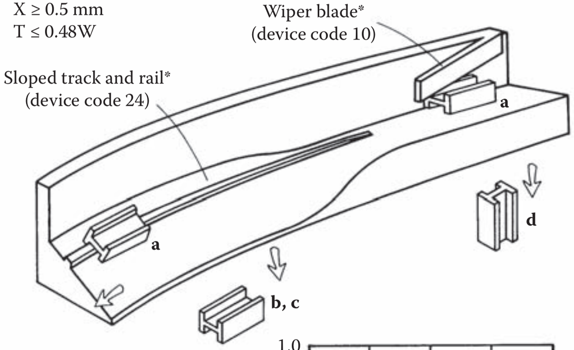
PART CODE 8 0 4

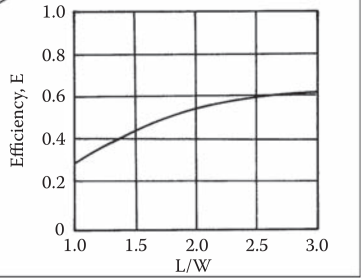


Part orientations



X ≥ 0.5 mm
T ≤ 0.48W





Feed rate = $\frac{v}{L} \times E$

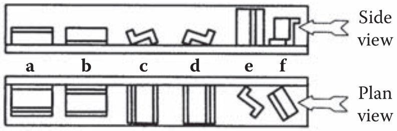
where:

v = Conveying velocity
E = Efficiency

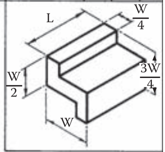
*For devices see section D3

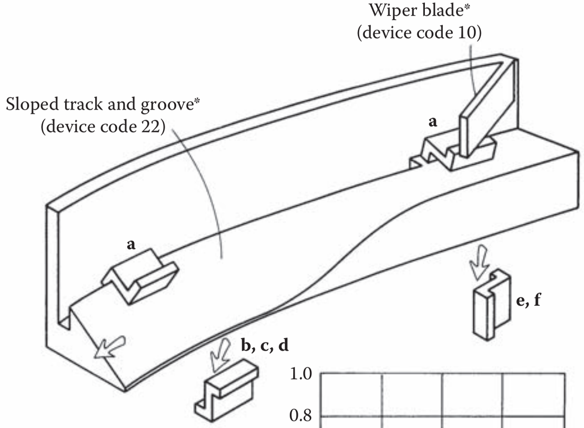
VIBRATORY BOWL FEEDER

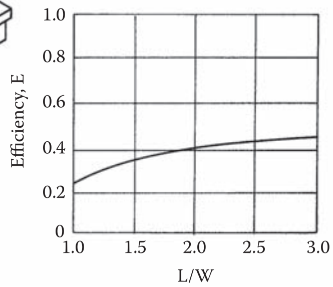
PART CODE 8 1 0



Part orientations







Feed rate = $\frac{v}{L} \times E$

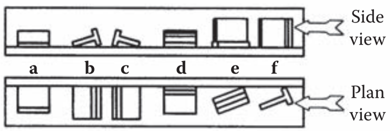
where:

v = Conveying velocity
E = Efficiency

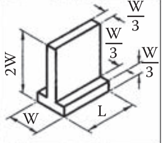
*For devices see section D3

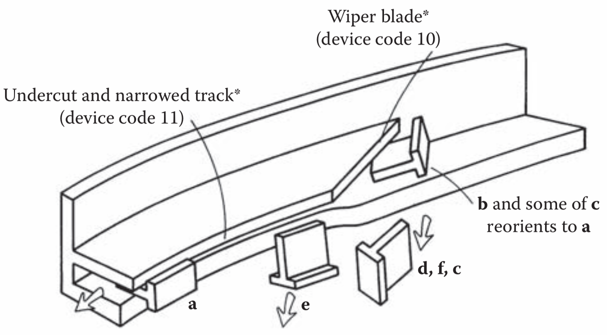
VIBRATORY BOWL FEEDER

PART CODE 8 1 1



Part orientations





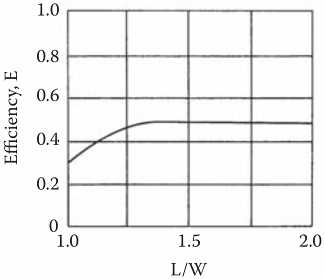
Wiper blade* (device code 10)
Undercut and narrowed track* (device code 11)
b and some of c reorients to a
d, f, c
e
a

Feed rate = $\frac{v}{L} \times E$

where:

V = Conveying velocity

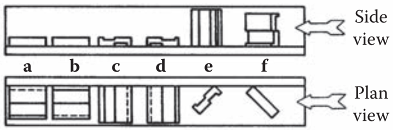
E = Efficiency



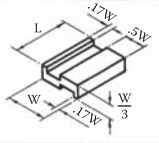
*For devices see section D3

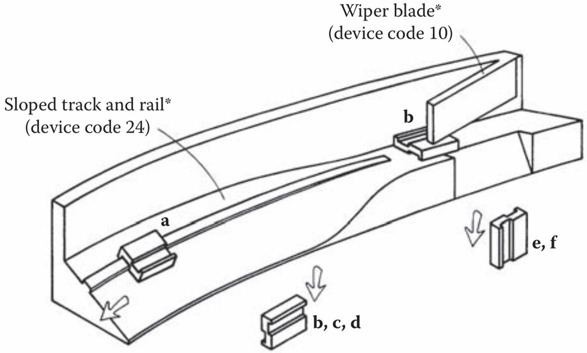
VIBRATORY BOWL FEEDER

PART CODE 8 1 3



Part orientations





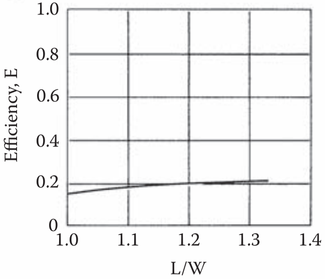
Wiper blade* (device code 10)
Sloped track and rail* (device code 24)
b
a
e, f
b, c, d

Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

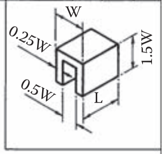
E = Efficiency



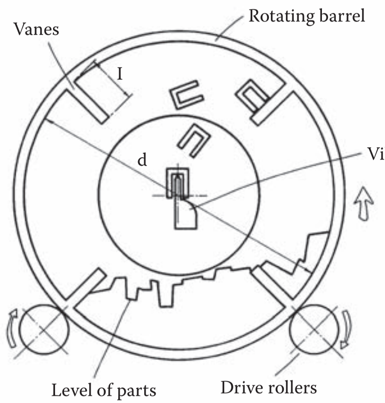
*For devices see section D3

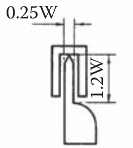
TUMBLING BARREL FEEDER

PART CODE	8	1	4



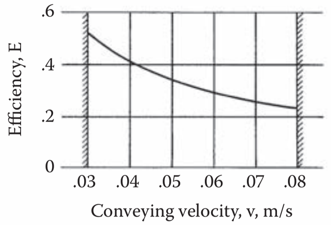
$\frac{d}{W} = 13$ $\frac{l}{W} = 1.8$ $\frac{\text{Length of barrel}}{d} = 1.2$





Vibratory rail

$1.0 < \frac{L}{W} < 1.2$



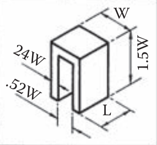
Feed rate $= \frac{E \times v}{L}$

where:

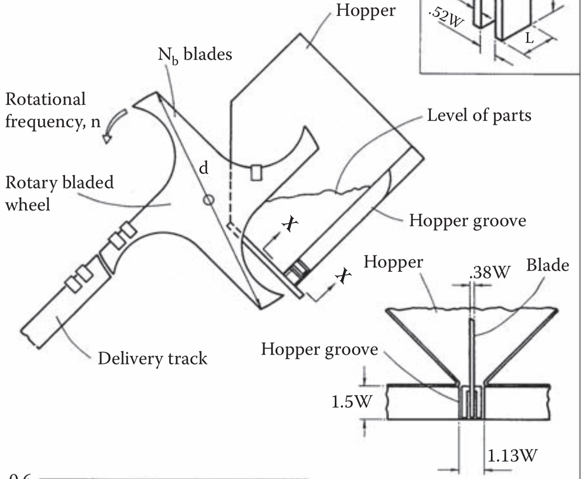
E = Efficiency
v = Conveying velocity on vibratory rail
L = Part length

ROTARY CENTERBOARD HOPPER FEEDER

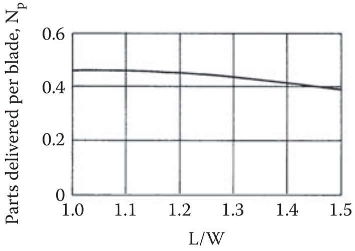
PART CODE	8	1	4



$\frac{d}{W} = 24$



Enlarged view on X-X



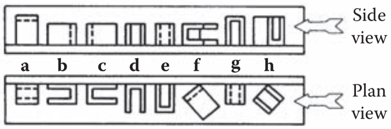
Feed rate $= N_p \times N_b \times n$

where:

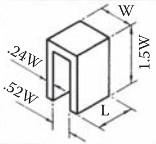
N_p = Parts delivered per blade
N_b = Number of blades
n = Rotational frequency

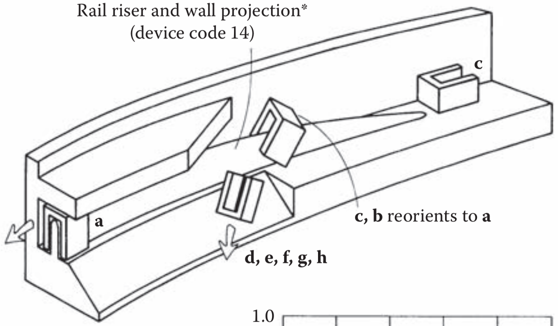
VIBRATORY BOWL FEEDER

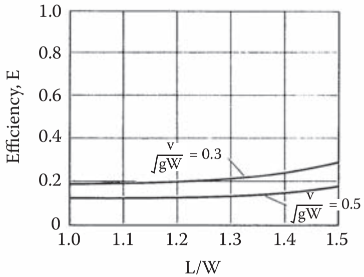
PART CODE	8	1	4



Part orientations







Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

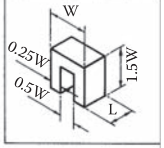
E = Efficiency

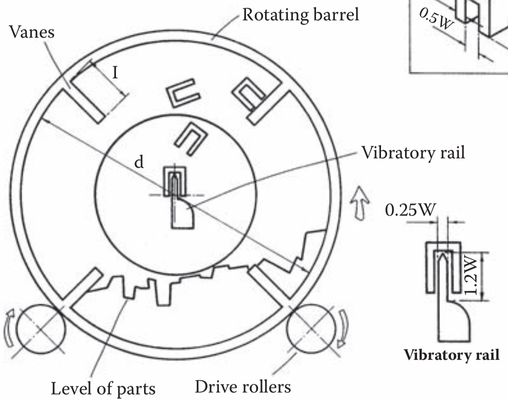
*For devices see section D3

TUMBLING BARREL FEEDER

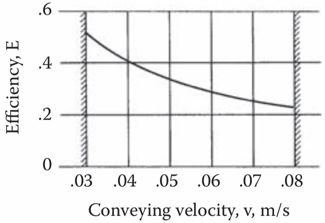
PART CODE	8	1	5

$\frac{d}{W} = 13 \quad \frac{l}{W} = 1.8 \quad \frac{\text{Length of barrel}}{d} = 1.2$





$0.4 < \frac{L}{W} < 1.0$



Feed rate = $\frac{E \times v}{L}$

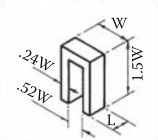
where:

E = Efficiency

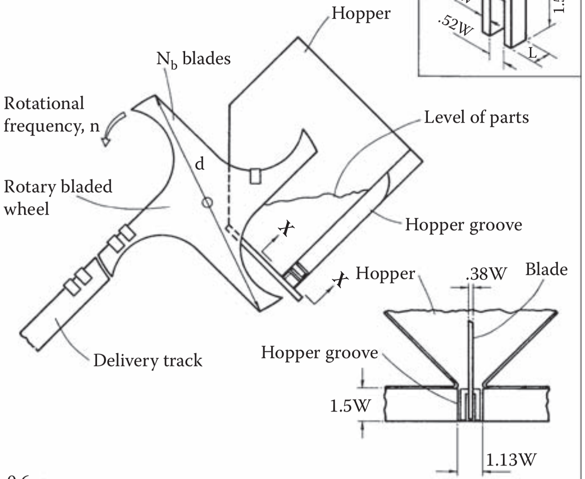
v = Conveying velocity on vibratory rail

L = Part length

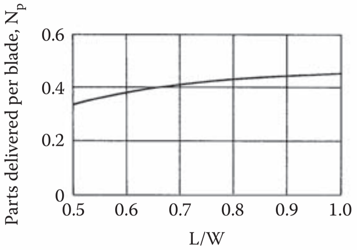
ROTARY CENTERBOARD HOPPER FEEDER	PART CODE	8	1	5



$\frac{d}{W} = 48$



Enlarged view on X-X

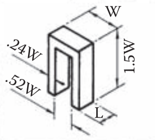


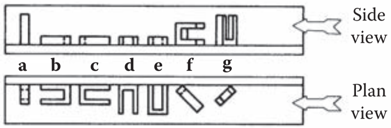
Feed rate = $N_p \times N_b \times n$

where:

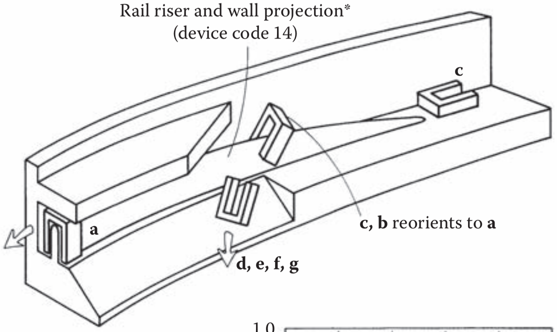
N_p = Parts delivered per blade
N_b = Number of blades
n = Rotational frequency

VIBRATORY BOWL FEEDER	PART CODE	8	1	5





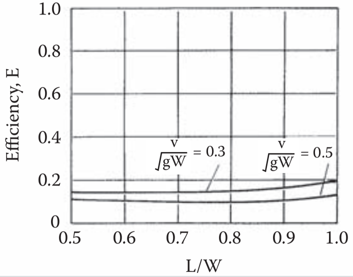
Part orientations



Feed rate = $\frac{v}{L} \times E$

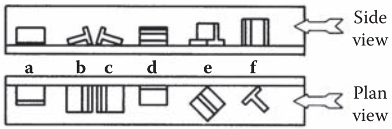
where:

v = Conveying velocity
E = Efficiency

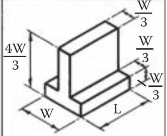


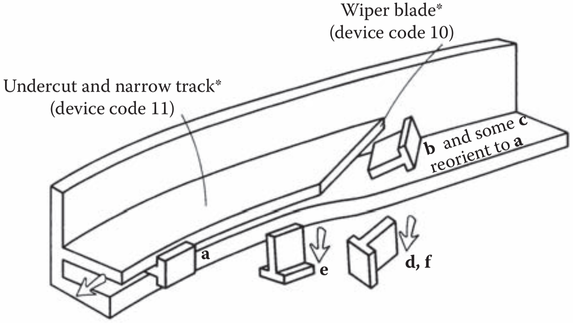
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	8	2	0



Part orientations



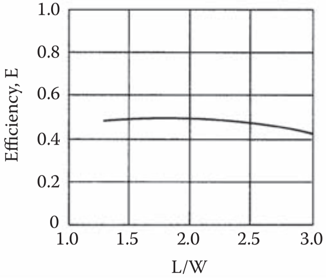


Feed rate = $\frac{v}{L} \times E$

where:

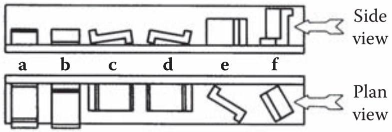
v = Conveying velocity

E = Efficiency

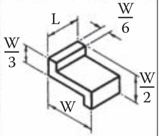


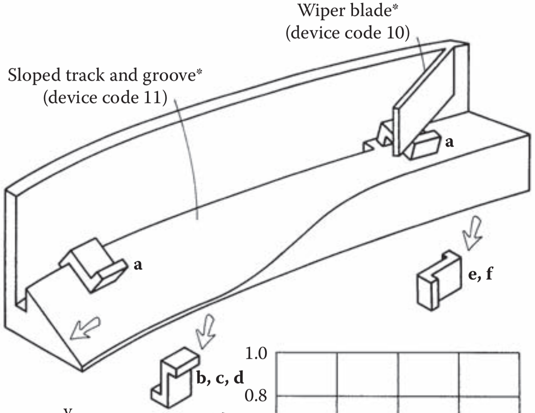
*For devices see section D3

VIBRATORY BOWL FEEDER	PART CODE	8	2	1



Part orientations



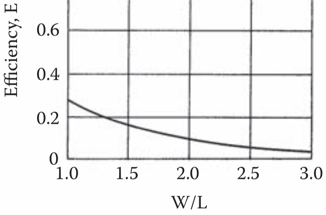


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

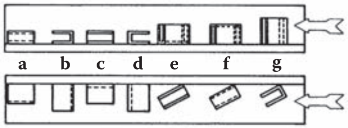
E = Efficiency



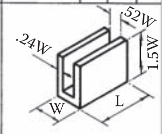
*For devices see section D3

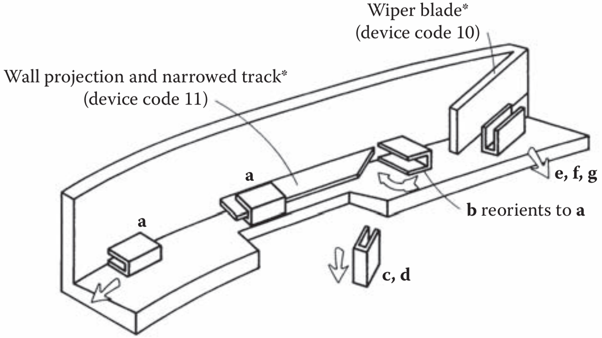
VIBRATORY BOWL FEEDER

PART CODE	8	2	3



Part orientations



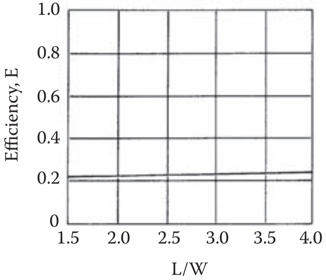


Feed rate $= \frac{v}{L} \times E$

where:

v = Conveying velocity

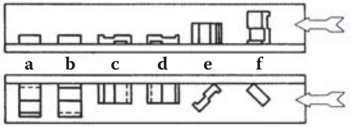
E = Efficiency



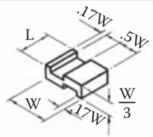
*For devices see section D3

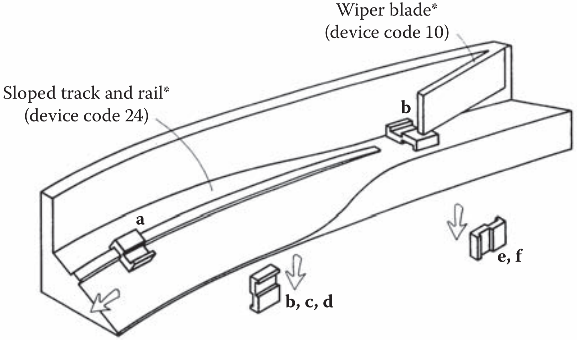
VIBRATORY BOWL FEEDER

PART CODE	8	2	4



Part orientations



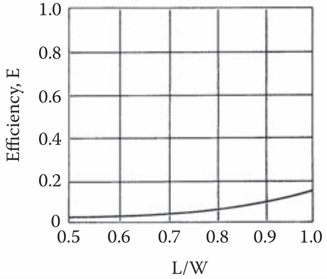


Feed rate $= \frac{v}{L} \times E$

where:

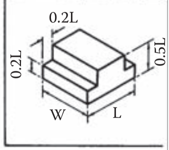
v = Conveying velocity

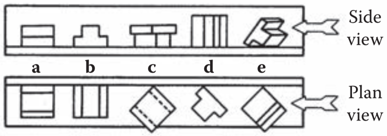
E = Efficiency



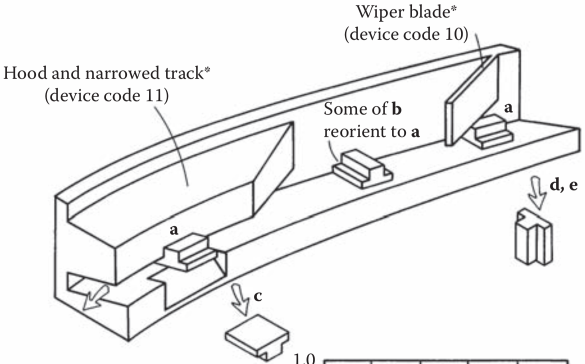
*For devices see section D3

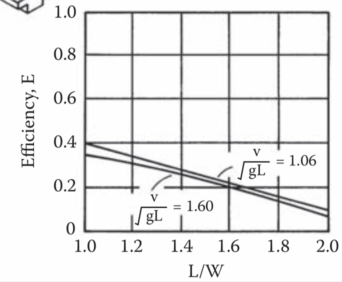
VIBRATORY BOWL FEEDER	PART CODE	8	3	1





Part orientations





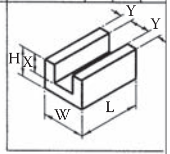
Feed rate = $\frac{v}{L} \times E$

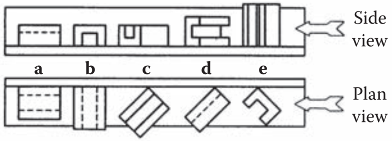
where:

v = Conveying velocity
E = Efficiency

*For devices see section D3

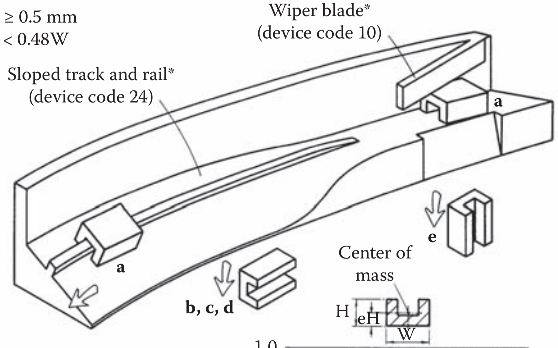
VIBRATORY BOWL FEEDER	PART CODE	8	3	3

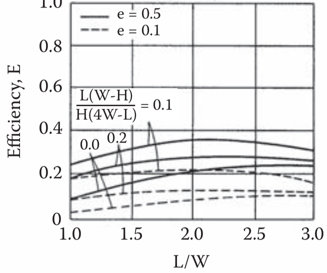




Part orientations

X ≥ 0.5 mm
Y < 0.48W





Feed rate = $\frac{v}{L} \times E$

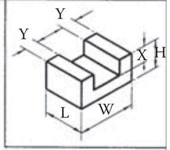
where:

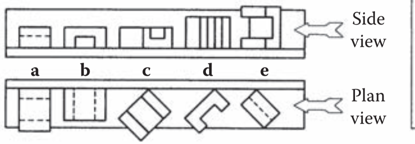
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

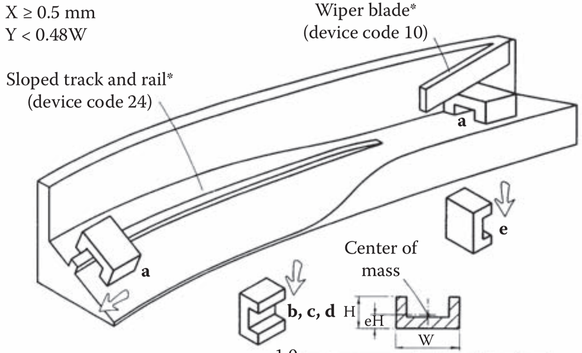
PART CODE	8	3	4

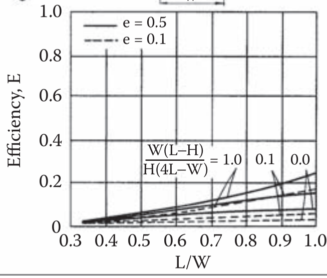




Part orientations

X ≥ 0.5 mm
Y < 0.48W





Feed rate = $\frac{v}{L} \times E$

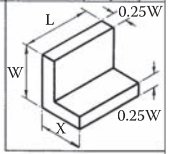
where:

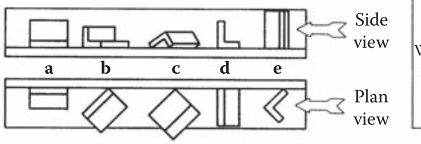
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

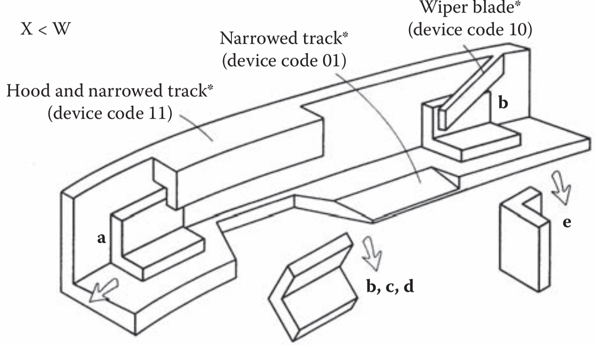
PART CODE	8	4	0

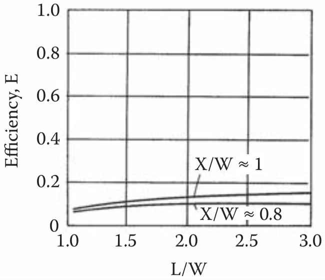




Part orientations

X < W





Feed rate = $\frac{v}{L} \times E$

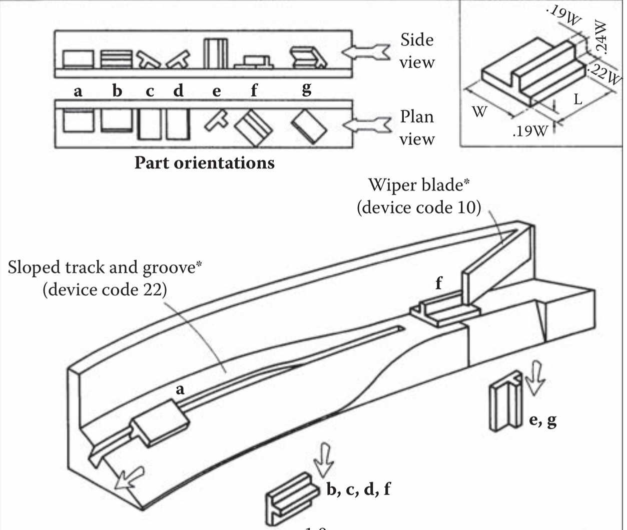
where:

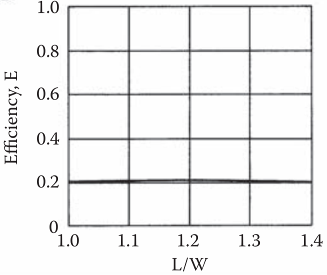
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE	8	4	0





Feed rate = $\frac{v}{L} \times E$

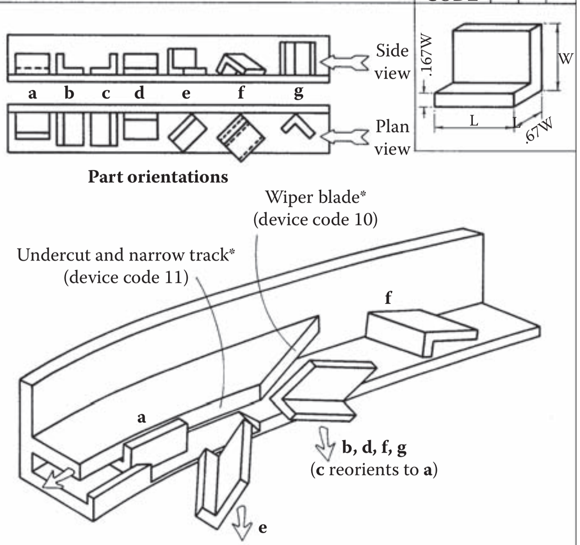
where:

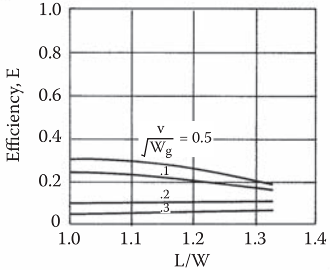
v = Conveying velocity
E = Efficiency

*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE	8	4	0





Feed rate = $\frac{v}{L} \times E$

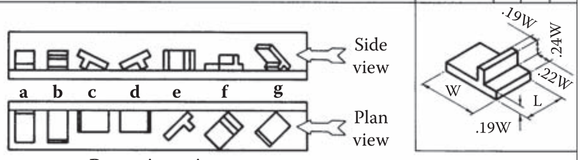
where:

v = Conveying velocity
E = Efficiency

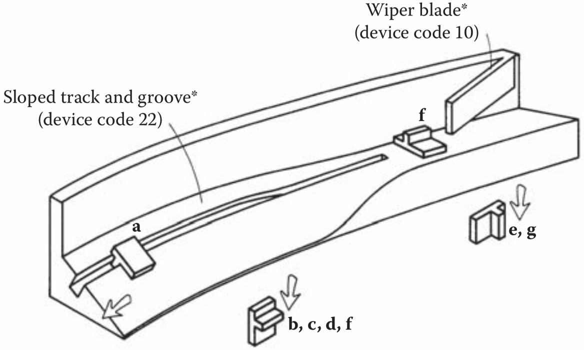
*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE 8 4 1



Part orientations

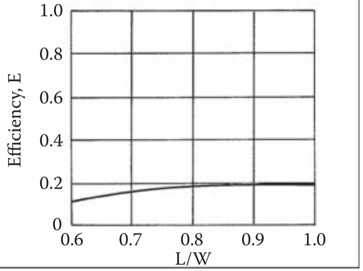


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

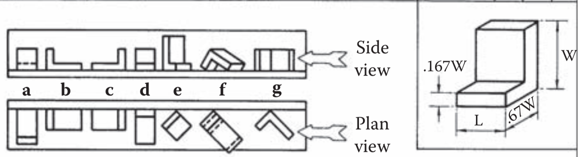
E = Efficiency



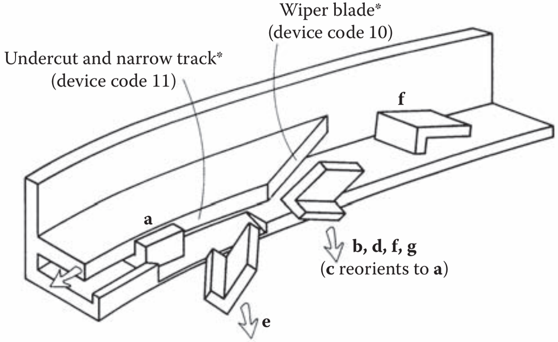
*For devices see section D3

VIBRATORY BOWL FEEDER

PART CODE 8 4 1



Part orientations

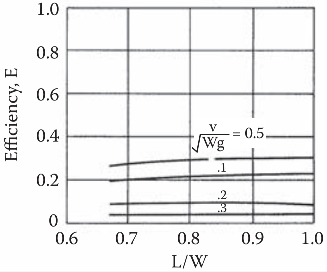


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

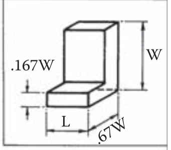
E = Efficiency

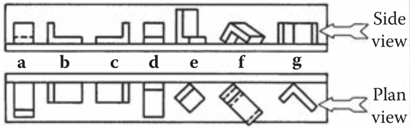


*For devices see section D3

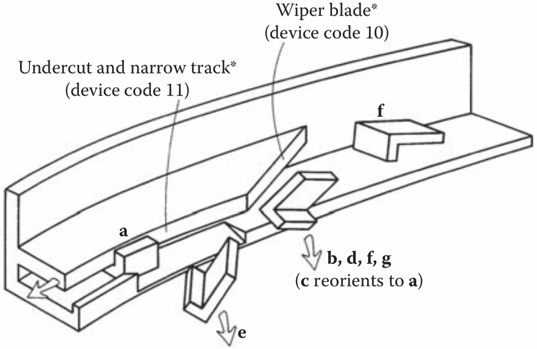
VIBRATORY BOWL FEEDER

PART CODE	8	4	2





Part orientations

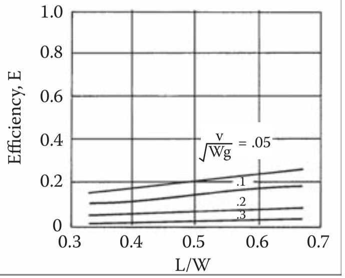


Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity

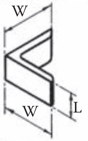
E = Efficiency



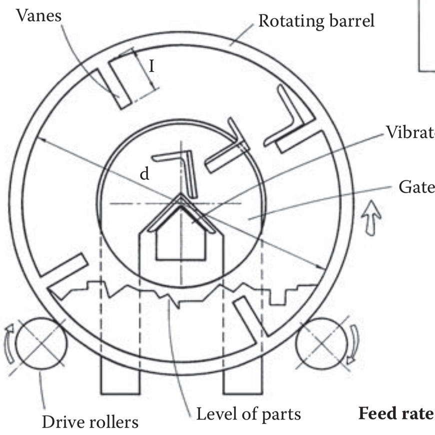
*For devices see section D3

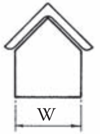
TUMBLING BARREL HOPPER FEEDER

PART CODE	8	4	2



$\frac{d}{W} = 6.47 \quad \frac{l}{d} = .155 \quad \frac{\text{Length of barrel}}{d} = 1.2$



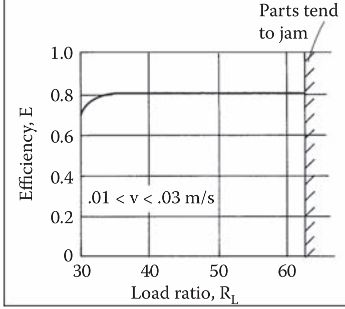


Vibratory rail

Feed rate = $\frac{E \times v}{L}$

where:

E = Efficiency
v = Conveying velocity on vibratory rail
L = Part length



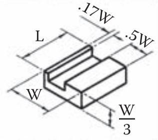
Load ratio, $R_L = \frac{L \times N}{W}$

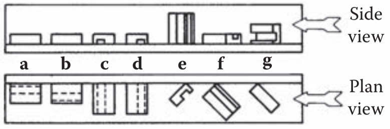
where:

N = Number of parts in hopper
W = Part width

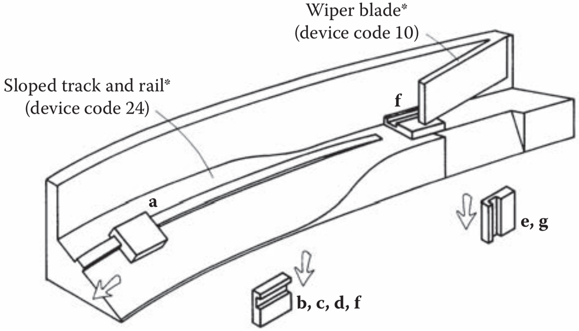
VIBRATORY BOWL FEEDER

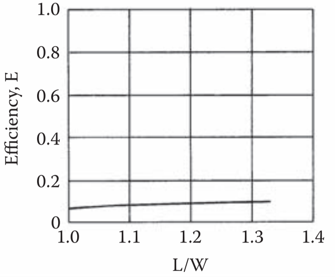
PART CODE	8	4	3





Part orientations





Feed rate = $\frac{v}{L} \times E$

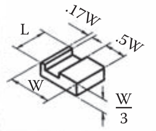
where:

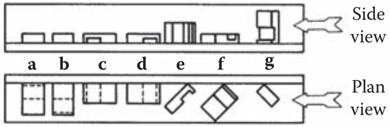
v = Conveying velocity
E = Efficiency

*For devices see section D3

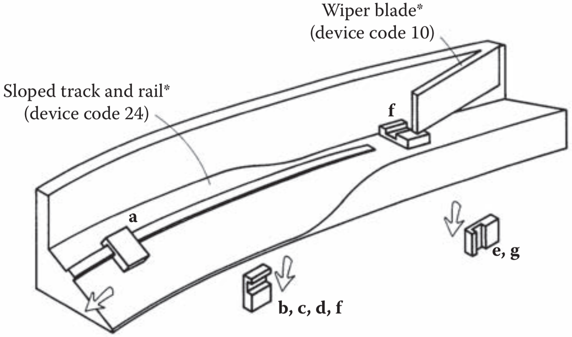
VIBRATORY BOWL FEEDER

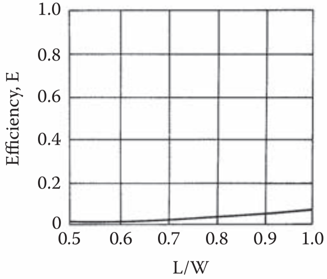
PART CODE	8	4	4





Part orientations





Feed rate = $\frac{v}{L} \times E$

where:

v = Conveying velocity
E = Efficiency

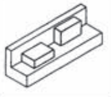
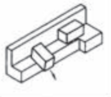
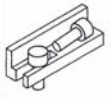
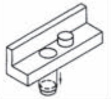
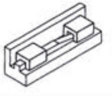
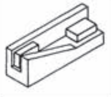
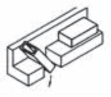
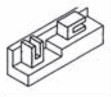
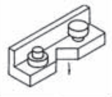
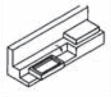
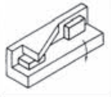
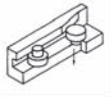
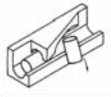
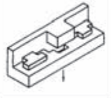
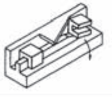
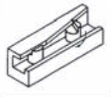
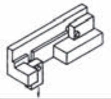
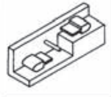
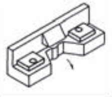
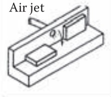
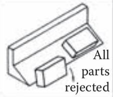
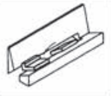
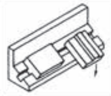
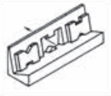
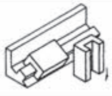
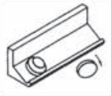
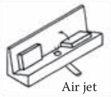
*For devices see section D3

D.3 ORIENTING DEVICES FOR VIBRATORY-BOWL FEEDERS

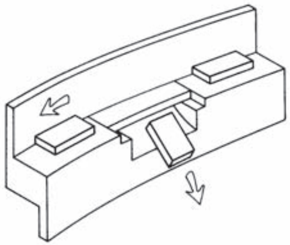
A device coding system is used to categorize orienting devices for vibratory-bowl feeders by their important characteristics. The purpose of the code is to provide a systematic method for listing orienting devices and arranging the data sheets in this section. The first digit of the 2-digit code represents the basic device configuration (flat or sloped track with or without a wall projection). The second digit is used to distinguish the various device modifications. Samples of devices with their various codes are shown below.

SECOND DIGIT

FIRST DIGIT

	Wide track **0**	Narrowed track **1**	Slot or groove **2**	Silhouette **3**	Rail **4**	Ledge or Edge Riser **5**	Gap **6**	Step **7**	Cut out **8**	Other **9**
Flat track **0**										
Flat track with wall projection **1**										
Sloped track with or without wall projection **2**							**Note:** The conveying direction for all devices shown is from right to left on the track surface			

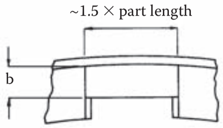
NARROWED TRACK	DEVICE CODE	0	1

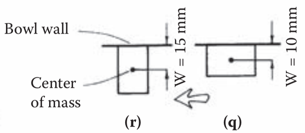


A narrowed track is generally employed to orient parts lengthwise end to end while permitting only one row to pass.

It is very suitable for parts having a length to width ratio or length to diameter ratio greater than 1.2.

The graph shows a plot of the ratio of the width of the narrowed track b to the distance from the bowl wall to the center of mass of the part w as a function of the conveying velocity v.



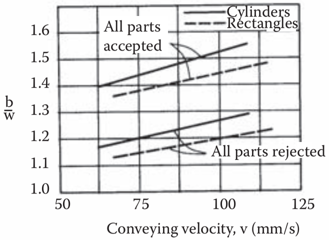


Rectangular parts 30 mm long × 20 mm wide are to be fed in orientation (q) at a conveying velocity of 100 mm/s.

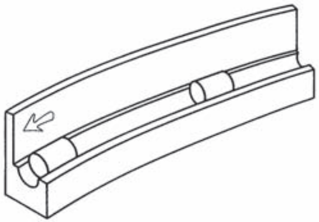
From the Graph

- The maximum value of b/w which will reject all specimens in orientation (r) is 1.19; thus, b = 17.8 mm.
- The minimum value of b/w to accept all specimens in orientation(q) is 1.42; thus, b = 14.2 mm.

Therefore, any value of b between 14.2 and 17.8 mm is acceptable.

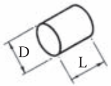


GROOVED TRACK	DEVICE CODE	0	2



A grooved track device is used to ensure a single line of cylindrical parts traveling end-to-end.

The range of L/D ratios for cylindrical parts which can be successfully handled by this device depends on the radius of the center line of the groove r. This range is



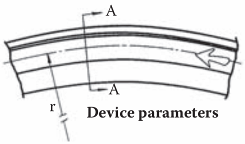
Part parameters

$$0.8 \leq \frac{L}{D} < \sqrt{1 + \frac{r}{D}}$$

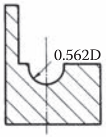
Example:
Given
D = 15 mm and r = 220 mm, then

$$L/D < \sqrt{\frac{220}{15}} \text{ or } 3.96$$

Thus this device will work for a range of cylindrical lengths from 12 to 59 mm when the part diameter is 15 mm.



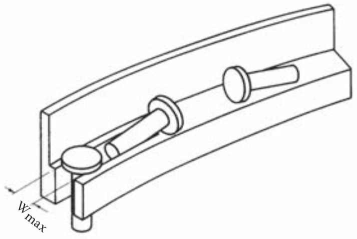
Device parameters



Section on A-A

SLOTTED TRACK

DEVICE CODE **0** **2**



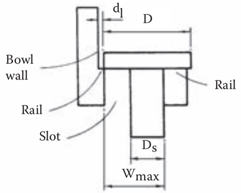
A slotted track is an orienting device used to provide a hanging position for headed parts. The headed part arriving at the slot with either the shank or the head leading will be delivered with the shank down.

The maximum width of the slot, W_{max}, is defined as the largest slot width that allows headed parts to hang on the rails with their rotational axis normal to the track surface, as shown in Fig. (a). The value of W_{max} is given by:

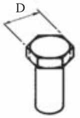
$$W_{max} = \frac{D + D_s}{2}$$

where D is the diameter of the head and D_s is the diameter of the shank. For hexagonal headed parts, D is the diameter of the inscribed cylinder of the head (Fig. (b)).

The width of the rail between the bowl wall and slot, d_l, is not critical but should be smaller than $D_s/2$.



(a)



(b)

Example:

Given a headed part with dimensions D=13 mm and D_s = 9 mm, the maximum width of the slot is

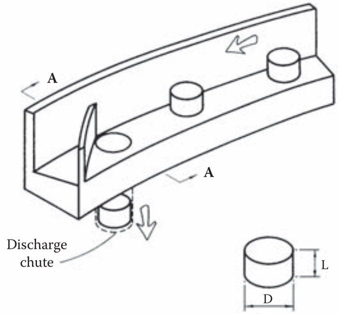
$$W_{max} = \frac{13 + 9}{2} = 11 \text{ mm}$$

and

$$d_l < 4.5 \text{ mm}$$

DISCHARGE HOLE I

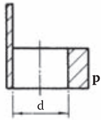
DEVICE CODE **0** **3**



Part parameters

Discharge hole I is a hole in the bowl track and is used to deliver plain discs or headed parts end-to-end.

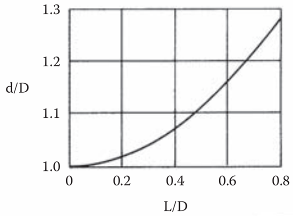
The important device parameter is the diameter of the discharge hole d. The maximum diameter of the hole that will preserve the orientation of the part when it has entered the hole can be obtained from the graph. Tests have shown that the divice is most effective when the diameter of the hole is close to its maximum value.



Device parameters

Section on A-A

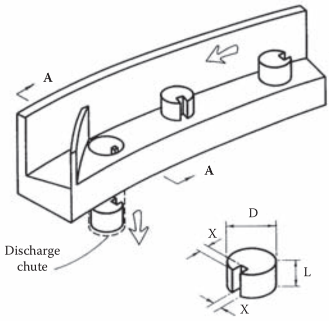
For a part ratio, L/D, less than 0.4, it is suggested that the parts be stacked in the discharge chute to increase the efficiency of the system. When the parts are stacked, the diameter of the discharge hole can be greater than the value obtained from the curve. The top part in the stack should be about one part length below the top of the discharge hole.



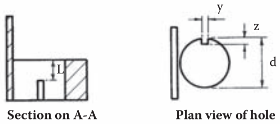
Example:

Given a disc with D = 12.7 mm and L = 7.62 mm, then L/D = 0.6. From the graph, d/D = 1.165 or d = 14.8 mm. Thus, the diameter of the discharge hole should be slightly less than 14.8 mm.

DISCHARGE HOLE II	DEVICE CODE	0	3

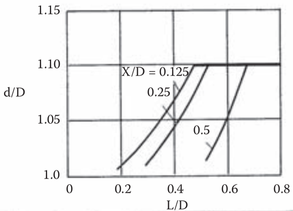


Part parameters



Section on A-A **Plan view of hole**

Device parameters



Discharge hole II is an orienting device used to feed discs and headed parts with longitudinal side grooves. Because of the vibration of the track, once the part enters the hole it rotates until the groove in the part and the key in the hole are aligned. The part is then delivered from the system in a single orientation.

The important device parameters are the diameter of the discharge hole d, the width of the key in the hole y, and the distance the key protrudes from the wall of the hole z.

The maximum diameter of the hole that will preserve the orientation of the part when it has entered the hole can be obtained from the graph. The optimum performance of the device is obtained when the diameter of the hole d is close to but not greater than the value obtained from the graph.

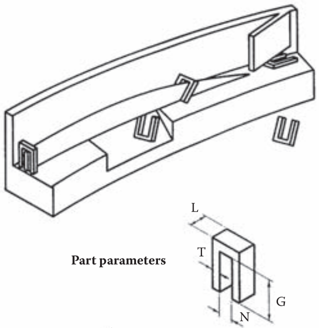
For a frequency of vibration of 60 Hz the part fails to rotate in the hole when the diametral clearance between the part and the hole wall becomes less than 0.03D. To increase the efficiency for this situation, it is suggested that the parts be stacked in the discharge chute. When the parts are stacked, the diameter of the discharge hole can be greater than the value obtained from the curve. The top part in the stack should be about one part length below the top of the discharge hole.

The smaller the ratio y/X, where X is the width of the groove in the part, the better the performance of the device. The value of z should be slightly less than x + d – D for optimum performance.

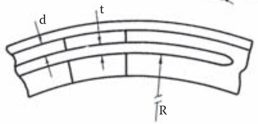
Example:

Given a part with D = 12.7 mm, L = 7.62 mm, and X = 3.175 mm, then L/D = 0.6 and X/D = 0.25. From the graph, d/D = 1.1 or d = 14 mm. Thus, the diameter of the discharge hole should be slightly less than 14 mm.

RAIL RISER	DEVICE CODE	0	4



Part parameters



Device parameters

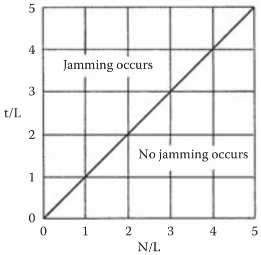
The rail riser is a ramp placed on the track parallel to the bowl wall to re-orient U-shaped parts. The slope of the ramp should be approximately 0.069 rads (4°) and rise along its entire length up to a maximum height equal to the diagonal across the groove in the conveying direction or $\sqrt{L_2 + G_2}$. The important design parameters are the rail thickness **t** and the distance between the bowl wall and rail **d**. These parameters can be determined from Figs. (a) and (b).

For cases when the part length is smaller than the gap between the bowl wall and the rail, a cut-out section between the rail and the bowl wall is necessary.

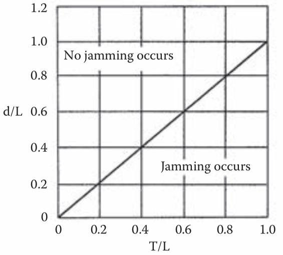
Example:

Given a U-shaped part with T= 4 mm, N = 10 mm, and L = 5 mm, then N/L = 2 and T/L = 0.8. Thus, from Fig. (a) t/L < 2 and from Fig. (b) d/L > 0.8 or t < 10 mm and d > 4 mm.

(a)

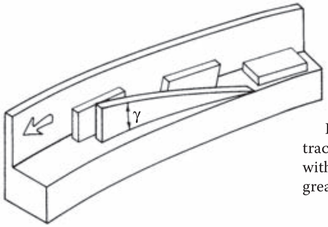


(b)



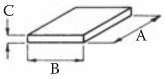
EDGE RISER I

DEVICE CODE **0 5**

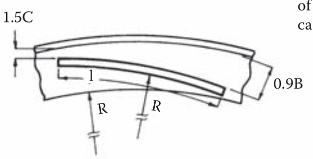


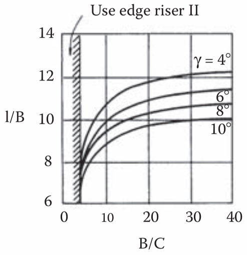
Edge riser I is a ramp placed on the track to re-orient rectangular prisms with a width to thickness ratio, B/C, greater than 4.

A > B > C
A ≤ 3B
B > 4C



The important design parameters are the ramp angle γ and the length of the ramp l. The length of the ramp can be determined from the graph.



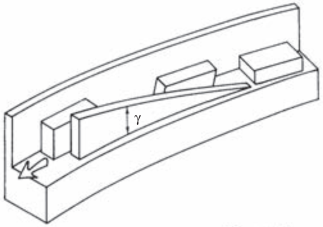


Example:

Given a part with dimensions A = 45 mm, B = 30 mm and C = 3 mm, then B/C = 10. For a ramp angle, γ = 6°, l/B = 10 from the graph. Thus the required ramp length is 300 mm.

EDGE RISER II

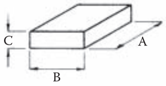
DEVICE CODE **0 5**

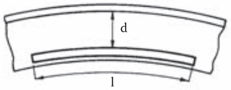


Edge riser II is a ramp placed on the track to re-orient rectangular prisms with a width to thickness ratio, B/C, of 4 or less.

The important design parameters are the distance of the ramp to the bowl wall d, the ramp angle γ, and the length of the ramp l.

A > B > C
A ≤ 3B
B ≤ 4C



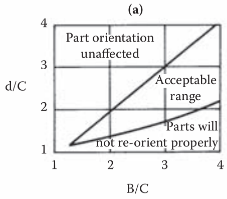


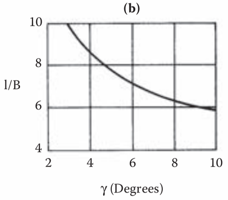
Example:

Given a part with dimensions A = 30 mm, B = 25 mm and C = 10 mm, then B/C = 2.5.

From Fig. (a) the acceptable range for d/C is between 1.5 and 2.5. Thus, an appropriate value for d is 20 mm.

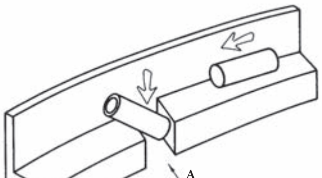
For a ramp angle, γ = 6°, l/B = 7.1 from Fig. (b). Thus the required ramp length is 178 mm.



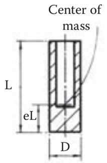


GAP

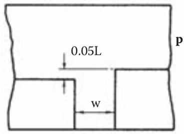
DEVICE CODE 0 6



Part parameters



Device parameters



View in direction of arrow A

The gap device is used to feed and orient cylindrical parts with a displaced center of mass. A part traveling on the track with its longitudinal axis in the conveying direction will fall into the gap heavy end first.

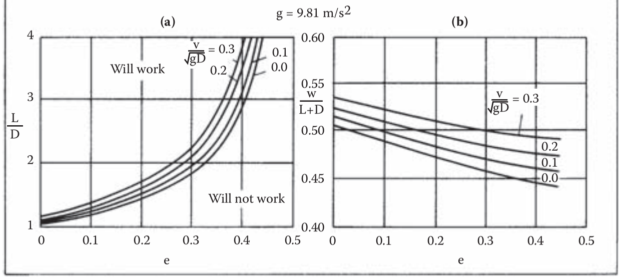
The suitability of this device for a particular part geometry and conveying velocity is defined in Fig. (a).

Example:

Given D = 10 mm, L = 30 mm, e = 0.2 and v = 50 mm/s; then L/D = 3 and $\frac{v}{\sqrt{gD}} = 0.16$. From Fig. (a) the geometry of the part falls within the working zone. The best gap width w to orient parts traveling either heavy end first or light end first is found in Fig. (b).

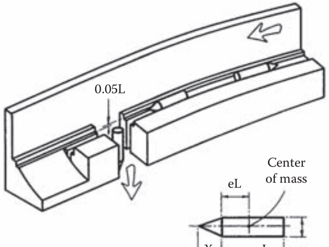
$$\frac{w}{L + D} = 0.49$$

Therefore, the best gap width is 19.6 mm.



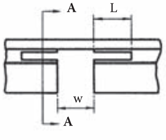
SHAPED GAP I

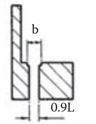
DEVICE CODE 0 6



Restriction b ≥ D + 0.2 (L + X)

Part parameters





Section on A-A

Device parameters

The shaped gap l is a device used to feed and orient cylinders with a displaced center of mass and a conical projection on one end. The displaced center of mass, which may not be due only to the conical projection, causes the cylinders to fall point first into the gap.

For proper operation of the device, the part must have a minimum length to diameter ratio L/D as determined from Fig. (a). This minimum L/D value is a function of the conveying velocity v, the ratio e of the location of the center of mass to the length of the main part of the cylinder, and X/D the projection length to diameter ratio.

The important design parameter is the width of gap w. If it is determined that a part can be fed and oriented with this device, the gap width is determined from Fig. (b).

Example:

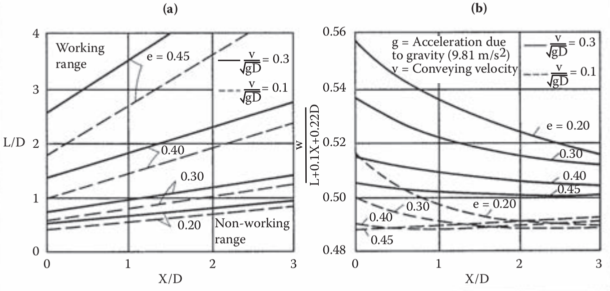
Given a cylinder with L = 20 mm, X = 10 mm, D = 10 mm, e = 0.3 and v = 70 mm/s; then L/D = 2.0, X/D = 1.0, and

$$\frac{v}{\sqrt{gD}} = \frac{0.07}{\sqrt{(9.81)(0.01)}} = 0.22.$$

From Fig. (a) the minimum acceptable L/D value is 0.85 which is less than 2.0. This means that the device can be used for this cylinder. From Fig. (b),

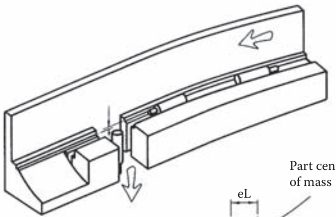
$$\frac{w}{L + 0.1X + 0.22D} = 0.51$$

and the width of the gap w should be 11.8 mm.

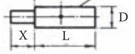


SHAPED GAP II

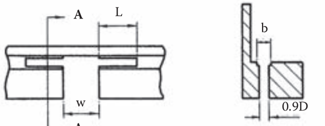
DEVICE CODE 0 6



Restriction b ≥ D + 0.2 (L + X)



Part parameters



Section on A-A

Device parameters

The shaped gap II is a device used to feed and orient cylinders with a displaced center of mass and a projection on one end. The displaced center of mass, which may not be due only to the projection on the end, causes the cylinders to fall projection end first into the gap.

The minimum length to diameter ratio of the part L/D is determined from Fig. (a). This minimum value of L/D is a function of the conveying velocity v, and the ratio e of the location of the center of mass to the length of the main part of the cylinder.

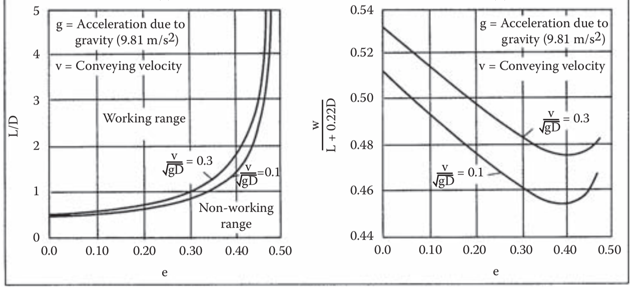
The important design parameter is the width of the gap w. If it is determined that a part can be fed and oriented with this device, the gap width is determined from Fig. (b).

Example:

Given a cylinder with L = 15 mm, X = 15 mm, D = 10 mm, e = 0.3 and v = 90 mm/s; then L/D = 1.5,

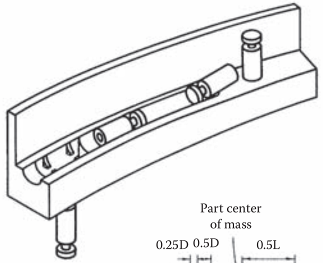
and $\frac{v}{\sqrt{gD}} = \frac{0.09}{\sqrt{(9.81)(0.01)}} = 0.29$.

From Fig. (a) the minimum acceptable L/D value is 0.95 which is less than 1.5. This means that the device can be used for the specified cylinder. From Fig. (b) $\frac{w}{L + 0.22D} = 0.482$ and the width of the gap w should be 8.29 mm.



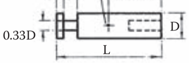
SHAPED GAP II

DEVICE CODE 0 6

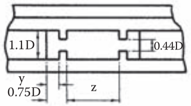


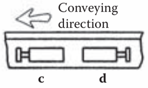
Restrictions

y < 0.5L − 0.75D
z = 0.5L − 0.6D



Part parameters





Part orientations

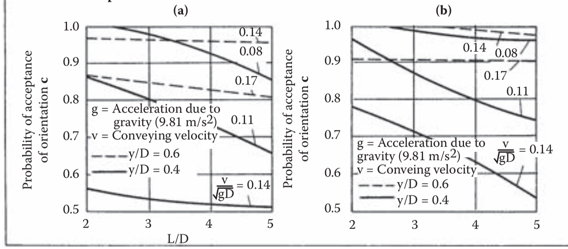
The shaped gap III is a device used to feed and orient cylinders with a concentric reduction in diameter or a neck. The presence or absence of a displaced center of mass does not affect the performance of the device.

The important design parameter is the length of the end portion of the gap y. The optimum length of the center portion of the gap z is given by the restriction.

Example:

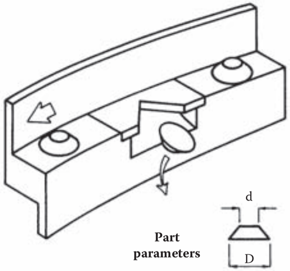
Given a cylinder with L = 35 mm, D = 10 mm, and v = 50 mm/s; then L/D = 3.5 and the gap width z = 0.5L − 0.06D = 16.9 mm. If a value of y/D = 0.06 were chosen, then the length of the end portion of the gap y = 6.0 mm and the value of the dimensionless velocity $\frac{v}{\sqrt{gD}} = \frac{0.050}{\sqrt{(9.81)(.01)}} = 0.16$ From Fig. (a) 0.88 of the parts that are in orientation **c** will be accepted and from Fig. (b) 0.94 of the parts that are in orientation **d** will be accepted.

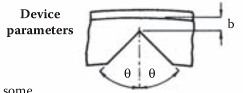
Device parameters

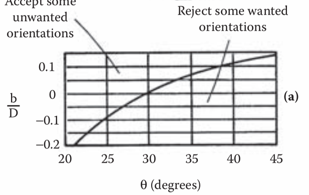


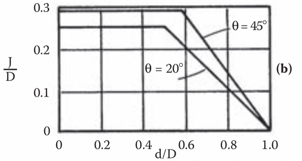
V CUT-OUT

DEVICE CODE 0 8









J = Maximum acceptable effective distance the part hops during each vibration cycle.

The V cut-out orienting device is a triangular notch in the track that is used to reject a part traveling on its small circular top. A part traveling on its larger circular base will pass over the device.

The important design parameters of the device are the half-angle of the cut-out θ and the distance b from the apex of the triangle to the bowl wall. The magnitudes of these parameters can be determined from Fig (a).

The device is completely effective if the effective distance the part hops J is less than the value determined using Fig (b). This effective hop is a function of the geometry of the feeder as well as its amplitude and frequency of vibration values of J for given feeding conditions can be obtained from Chapter 3 of this text

Example:

Given D = 40 mm and d = 32 mm. suppose θ = 35° Then from Fig. (a)

$$\frac{b}{D} = 0.07$$

and

$$b = 2.8\text{ mm}$$

Also since $\frac{d}{D} = 0.8$ then from Fig. (b)

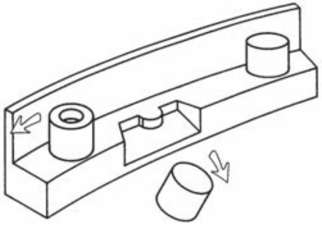
$$\frac{J}{D} = 0.13$$

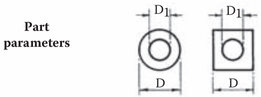
and therefore

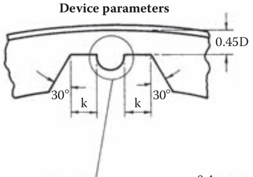
$$J = 5.2\text{ mm}$$

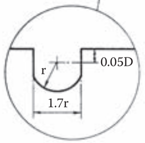
SCALLOP I

DEVICE CODE 0 8







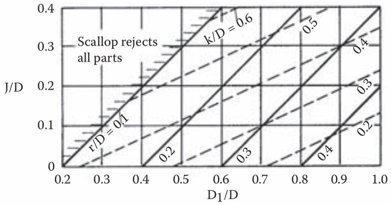


Scallop I is an orienting device used to reject hollow-ended parts such as cup shaped parts which are traveling with their open end down. A part traveling with its open end up will pass over the device.

The design of the complete device is shown to the left. The important design parameters of the device are k, the minimum distance from the projection to the edge of the cut-out and r, the maximum radius of the projection. The values of these parameters depend on the part shape and conveying speed and can be found from the graph. The hole in the part should be at least 0. $1D_1$ deep.

Example:

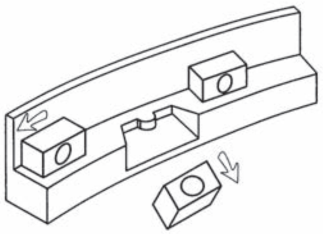
Cylindrical caps 10 mm in diameter with an 8 mm hole are fed past a scallop. The effective hop of the part J depends on the bowl feeder setting and its value can be found in Chapter 3.
For this example J = 1 mm. Thus, $D_1/D = 0.8$ and $J/D = 0.1$. From the graph $r/D = 0.35$ and $k/D = 0.25$ or r = 3.5 mm and k = 2.5 mm.



J = Maximum effective distance the part hops during each vibration cycle

SCALLOP II

DEVICE CODE | 0 | 8

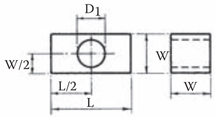


Scallop II is an orienting device used to reject square or nearly square prismatic parts with a centrally located through hole or a centrally located recess which is traveling with the opening down. A part with a through hole to the side will pass over the device. A part with a recess up or to either side will pass over the device. A recess should be at least $0.1D_1$ deep.

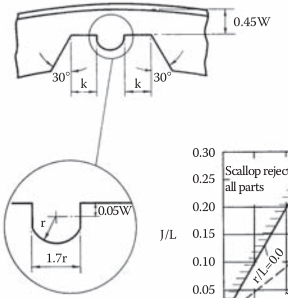
The important design parameters of the device are k, the minimum distance from the projection to the edge of the cut out and r, the maximum radius of the projection. The values of these parameters depend on the part shape and conveying speed and can be found from the graph. The design of the complete device is shown to the left.

Part parameters

$L > W$
$D_1 > 0.2W$

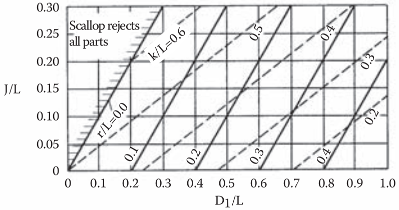


Device parameters



Example:

Long square prisms 20 mm in length and 10 mm on a side with a 5 mm diameter through hole are fed past a scallop. The effective hop of the part J depends on the bowl feeder setting and its value can be found in Chatper 3. For this example J = 1 mm. Thus, $J/L = 0.05$ and $D_1/L = 0.25$. From the graph $r/L = 0.1$ and $k/L = 0.44$ or r = 2.0 mm and k = 8.8 mm.



J = Maximum effective distance the part hops during each vibration cycle

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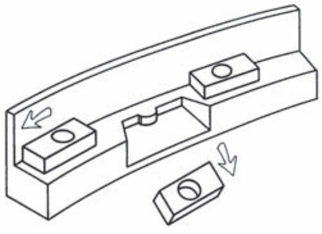
SCALLOP III

DEVICE CODE | 0 | 8



Scallop III can be used for various shapes not explicitly covered by Scallop I and Scallop II. Its most obvious user are for parts with an offset hole and parts with several holes which may or may not be symmetrically located. Scallop III covers these two cases.

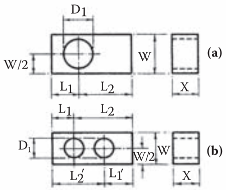
The design of the complete offset scallop device is shown to the left. The important design parameters are k, the minimum distance from the projection to the edge of the cut out and r, the maximum radius of the projection. The values of these parameters depend on the part shape and conveying speed and can be found from the graph.

Offset scallop part parameters

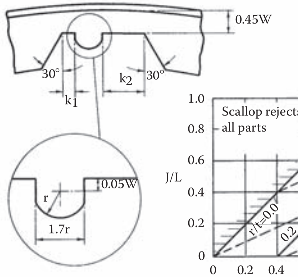
$W/2 < L_1 < L_2$
$0.83X < W < 5D_1$

Series scallop part parameters

$W/2 < L_1 < L_2$
$0.83X < W < 5D_1$



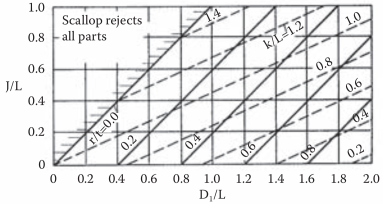
Device parameters



Example:

Square prisms 26 mm long and 10 mm wide with an 8 mm diameter hole located 10 mm from the left end are fed past a scallop. The effective hop of the part J depends on the bowl feeder setting and its value can be found in Chapter 3. For this example J = 1 mm. Thus, $J/L_1 = 0.1$, $D_1/L_1 = 0.8$. $J/L_2 = 0.06$ and $D_1/L_2 = 0.5$. From the graph $r_1/L_1 = 0.35$. $k_1/L_1=0.75$, and $r_2/L_2 = 0.22$, $k_2/L_2 = 0.85$ or $r_1 = r_2 = 3.5$ mm. $k_1 = 7.5$ mm and $k_2 = 13.6$ mm. Note that the values for r are always identical.

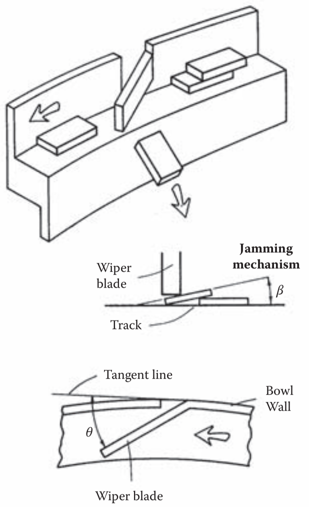
For a part with several holes the scallop may be designed by considering each hole separately and then applying the design criteria for the offset scallop. The designs can then be superimposed.

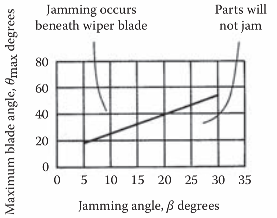


J = Maximum effective distance the part hops during each vibration cycle.

WIPER BLADE

DEVICE CODE | 1 | 0





A wiper blade is a device commonly used to ensure a single level of parts by rejecting those parts which are resting upon others. It is also used to reject those parts which are travelling in the taller orientation.

Jamming can occur with this device if a part becomes wedged beneath the wiper blade. This jamming mechanism is a function of the part geometry.

The maximum acceptable wiper blade angle θ_{max} can be determined from the graph and is a function of the part geometry represented by the jamming angle β.

Example: Flat washers 20 mm in diameter and 8 mm thick have a minimum β value of:

$$\beta = \sin^{-1}\left(\frac{8}{20}\right) = 23.6 \text{ degrees.}$$

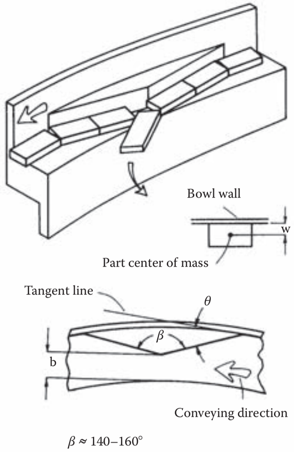
From the graph this corresponds to a θ_{max} value of 42 degrees.

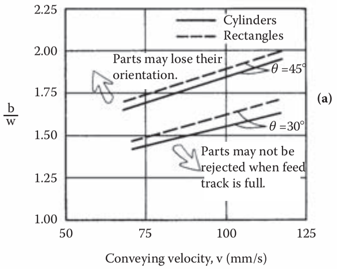
The maximum clearance between the passing layer of parts and the wiper blade is approximately equal to the thickness of the part. The minimum clearance can be determined from Chatper 3 and is a function of the conveying velocity.

The effect of θ on the feeding velocity can be considered negligible for values of θ up 60 degrees.

PRESSURE BREAK

DEVICE CODE | 1 | 0





A pressure break is a triangular projection on the bowl wall which is used to reject parts back into the bowl when the delivery chute is full. It thus prevents large pressures from developing in the feed track.

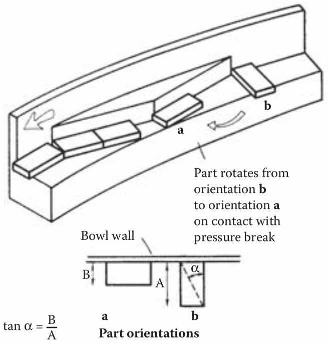
The important design parameters are the angle between the tangent line to the bowl wall and the leading edge θ, the apex angle between the leading and trailing edges β, the distance between the apex of the pressure break and the edge of the track b, and the distance from the center of mass of the part to the bowl wall w.

The design of a pressure break will depend on the shape of the part to be fed. For cylindrical and rectangular parts the pressure break works best when the value of θ is between 30° and 45°. When θ exceeds 45° parts may lose their orientation while values below 30° might not cause parts to be rejected when the feed track is full. The graph shows the relationship between the conveying velocity and the minimum value of b/w which will just allow all parts to pass when the feed track is not yet full.

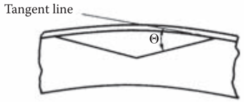
Example:
Rectangular parts with a width of 20 mm are to be fed past a pressure break. A θ of 30° and a conveying velocity of 75 mm/s are chosen. From the graph b/w = 1.49 is determined. As w = 10 mm, b = 1.49 × 10 mm = 14.9 mm.

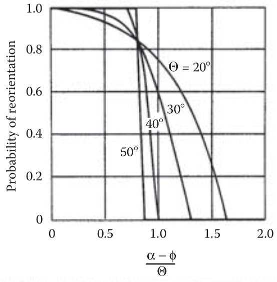
PRESSURE BREAK (Continued)

DEVICE CODE 1 0


b
a
Part rotates from orientation **b** to orientation **a** on contact with pressure break
Bowl wall
B
A
α
a
b
Part orientations

$\tan\alpha = \frac{B}{A}$





A pressure break is a triangular projection on the bowl wall which is used to reject parts back into the bowl when the delivery chute is full. A pressure break can sometimes be used as an orienting device and it is this aspect of the pressure break design that is the subject of this data sheet.

The important design parameters determining the reorienting effect of the pressure break are the angle Θ between the tangent line to the bowl wall and the leading edge of the pressure break, the friction angle ϕ between the device and the part and the part angle α defined in the figure. The probability of reorientation for a part can be obtained from the graph.

Example:

Rectangular parts with dimensions A = 40 mm, and B = 20 mm are to pass a pressure break having an angle Θ of 20°. The coefficient of friction between the part and the pressure break is 0.3. For orientation b:

$$\alpha = \arctan \frac{20}{40} = 26.6°$$

$$\phi = \arctan 0.3 = 16.7°$$

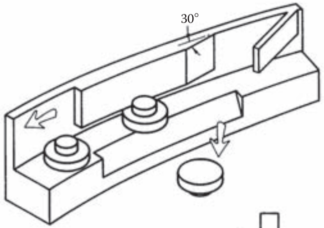
Hence

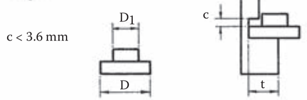
$$\frac{\alpha - \phi}{\Theta} = \frac{26.6 - 16.7}{20} = 0.493$$

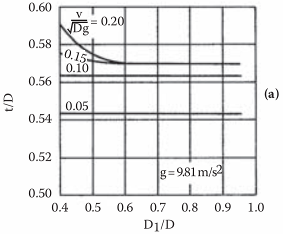
From the graph, the probability of parts changing from orientation b to orientation a is 0.93.

WALL PROJECTION AND NARROWED TRACK

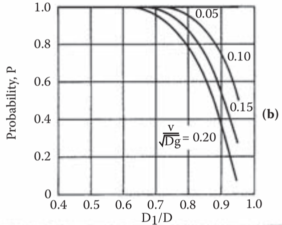
DEVICE CODE 1 1







(a)



(b)

The wall projection and narrowed track device is used to feed and orient parts with steps or grooves such as short headed parts. The projection has the same radius as the track so that the track width remains constant. A short headed part traveling on its larger end will pass through the device but other orientations will be rejected back into the bowl.

The track width is set to reject all the parts traveling on their smaller end. The maximum track width t for a particular conveying velocity v and part shape can be determined from Fig. (a).

Example:

Suppose D = 20 mm, D_1 = 16 mm and v = 90 mm/s; then $D_1/D = 0.8$ and

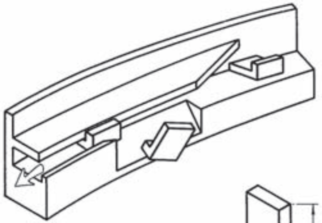
$$\frac{v}{\sqrt{Dg}} = \frac{.09}{\sqrt{(.02)(9.81)}} = 0.20$$

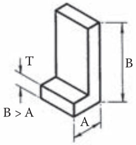
From Fig. (a), t/D = 0.57 and t = 11.4 mm.

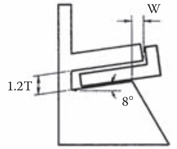
The performance of this device is defined as the probability P that a correctly oriented part will pass through the device when the track width t is set in accordance with Fig. (a). This probability is shown in Fig. (b). For the previous example, 80 percent of the parts tavelling on their larger end willl pass through this device.

UNDERCUT AND NARROWED TRACK

DEVICE CODE	1	1





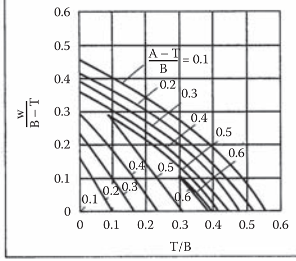


The undercut and narrowed track device is used to feed and orient L-shaped parts which have unequal sides. Only a part traveling on its larger side with the smaller side parallel to but away from the bowl wall will pass through the device, a part traveling in a similar attitude but on its smaller side will be rejected.

The important design parameter for the device is the length of overhang w above the narrow track. The maximum and minimum values of w can be found from the graph. With values of w greater than the maximum desired parts will be rejected. With values of w less than the minimum, unwanted parts will be accepted.

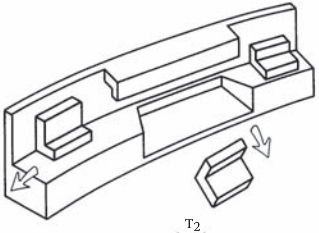
Example:

Suppose A = 12 mm, B = 20 mm and T = 4 mm; then T/B = 0.20 and (A − T)/B = 0.40. From the figure the maximum value of w/(B − T) is 0.24 and the minimum value of w/(B − T) is 0.05. Then the range for w is 0.8 mm to 3.84 mm.



HOOD AND NARROWED TRACK

DEVICE CODE	1	1

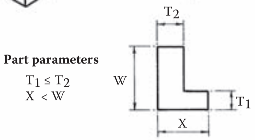


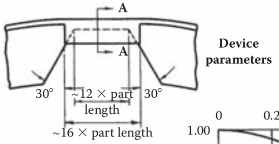
The hood and narrowed track orienting device is used to orient L-shaped parts with a difference in leg length. Parts in the taller orientation pass through the device unaffected while those in the shorter orientation are rejected.

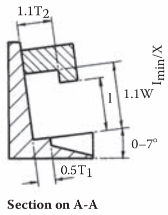
The important design parameter is the distance from the track surface to the hood overhang, I. The maximum and minimum values for I can be found from the graph. The design of the complete device is shown to the left.

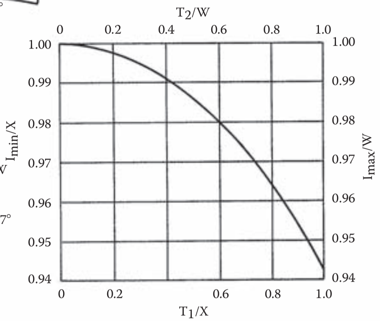
Example:

Suppose L-shaped parts are fed past a hood and narrowed track where X = 10 mm, W = 12 mm, T_1 = 2 mm and T_2 = 3 mm. Thus T_1 /X = 0.2 and T_2/W = 0.25. From the graph I_{min}/X = 0.998 and I_{max}/W = 0.997 or I_{min} = 9.98 mm and I_{max} = 11.96 mm. Thus a convenient value for I is 11 mm.



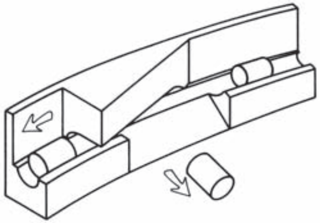






GROOVED TRACK AND HOOD

DEVICE CODE 1 2



A grooved track and hood device is used to ensure a single line of cylindrical parts traveling end-to-end. It rejects those parts which are traveling side by side.

The height of the hood h depends on the length L and diameter D of the part.

For
$0.8 \le \frac{L}{D} \le 1.02$ then $h = 1.02D$,
for
$1.02 < \frac{L}{D}$ then $1.02\,D < h < L$

Example:

Given a cylinder with
D = 15 mm and L = 18 mm
then
L/D = 1.2.
Thus,
15.3 mm < h < 18 mm
and a satisfactory hood height is 17 mm.

The range of L/D ratios for cylindrical parts which can be successfully handled by this device depends on the radius of the center line of the groove r. This range is

$$0.8 \le \frac{L}{D} < \sqrt{\frac{r}{D}}$$

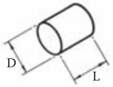
Example:
Given
D = 15 mm and r = 220 mm,
then
$L/D < \sqrt{220/15}$ or 3.8.

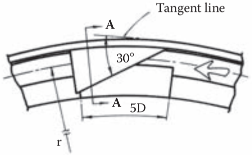
Thus, this device will work for a range of cylindrical lengths from 12 to 57 mm when the part diameter is 15 mm.

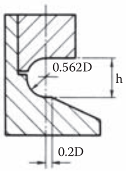
Restrictions $0.8 \le \frac{L}{D} < \sqrt{\frac{r}{D}}$

where:

r = Radius of the centerline of the groove



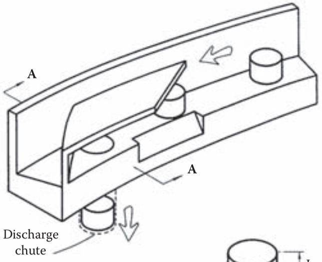




Section on A-A

HOODED DISCHARGE HOLE I

DEVICE CODE 1 3



Hooded discharge hole I is a hole in the bowl track and is used to deliver plain discs end-to-end.

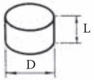
The important device parameters are the diameter of the discharge hole d and the clearance between the hood and track c.

The function of the hood is to preserve the orientation of the disc as it is entering the discharge hole and thereby prevent jamming. The maximum diameter d of the discharge hole that will preserve the orientation of the disc when it has entered the discharge hole can be obtained from the graph. Tests have shown that the device is most effective when the diameter of the hole is close to its maximum value.

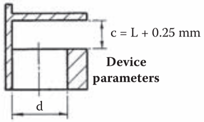
For a part ratio, L/D, less than 0.4, it is suggested that the parts be stacked in the discharge chute to increase the efficiency of the system. When the parts are stacked, the diameter of the discharge hole can be greater than the value obtained from the curve. The top part in the stack should be about one part length below the top of the discharge hole.

Example:

Given a disc where D = 12.7 mm and L = 7.62 mm, then L/D = 0.6. From the graph, d/D = 1.165 or d = 14.8 mm. Thus, the diameter of the discharge hole should be slightly less than 14.8 mm.

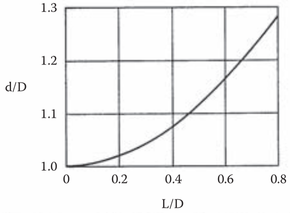


Part parameters



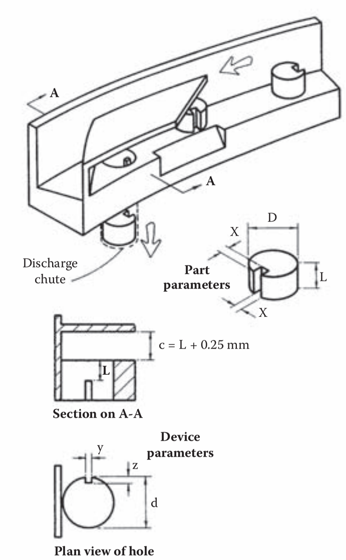
Device parameters

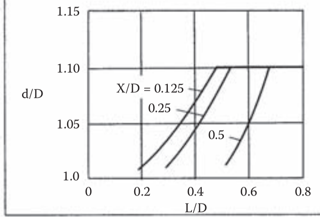
Section on A-A



HOODED DISCHARGE HOLE II

DIVICE CODE 1 3





Hooded discharge hole II is an orienting device used to feed discs with longitudinal side grooves. Because of the vibration of the track, once the part enters the hole it rotates until the groove of the part and the key in the hole are aligned. The part is then delivered from the system in a single orientation.

The important device parameters are the diameter of the discharge hole d, the clearance between the hood and the track c, the width of the key in the hole y and the distance the key protrudes from the wall of the hole, z.

The function of the hood is to preserve the orientation of the part as it is entering the discharge hole and thereby prevent jamming. The optimum performance of the device is obtained when the diameter of the hole d is close to but not greater than the value obtained from the graph.

For a frequency of vibration of 60 Hz the part fails to rotate in the hole when the diametral clearance between the part and the hole wall becomes less than 0.03D. To increase the efficiency for this situation, it is suggested that the parts be stacked in the discharge chute. When the parts are stacked, the diameter of the discharge hole can be greater than the value obtained from the curve. The top part in the stack should be about one part length below the top of the discharge hole.

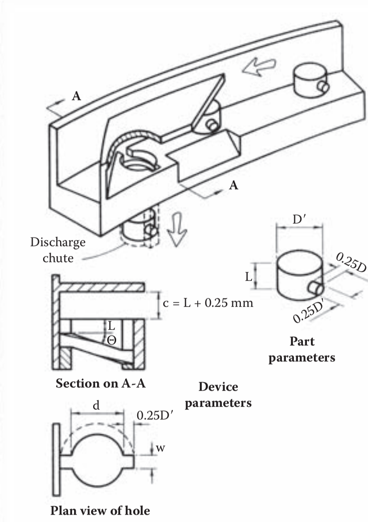
The smaller the ratio y/X, where X is the width of the groove in the part, the better the performance of the device. The value of z should be slightly less than X + d – D for optimum performance.

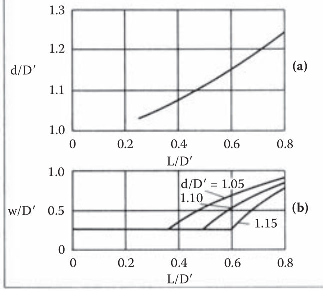
Example:

Given a part with D = 12.7 mm, L = 7.62 mm and X = 3.175 mm, then L/D = 0.6 and X/D = 0.25. From the graph, d/D = 1.1 or d = 14 mm. Thus, the diameter of the discharge hole should be slightly less than 14 mm.

HOODED DISCHARGE HOLE III

DEVICE CODE 1 3





Hooded discharge hole III is an orienting device used to feed discs with projections on their side surface. Because of the vibration of the track, once the part enters the hole it rotates until the axis of the projection reaches one of the two positions when it is perpendicular to the bowl wall. Except when the amplitude of vibration is large, the part tends to remain in one of these two positions. Therefore, two slots are machined on the inner surface of the hole. One slot runs parallel to the longitudinal axis of the discharge chute, the other slot is helical and connected to the straight one so that the parts are fed out of the system in a single orientation.

The important device parameters are the diameter of the discharge hole d, the clearance between the hood and the track c, the angle of the helical slot in the hole Θ and the width of the slot w.

The function of the hood is to preserve the orientaton of the part as it is entering the discharge hole and thereby prevent jamming. The maximum diameter of the discharge hole, d, that will prevent the part from jamming when it has entered the hole can be obtained from Fig. (a). The device is most effective when the diameter of the hole is close to its maximum value.

To prevent jamming while the part is passing through the discharge hole, the angle of the helical slot Θ is given by: Θ = arctan (L/D′). To preserve the orientation of the part while in the discharge hole, the maximum width of the slot w can be obtained from Fig. (b).

For a part ratio, L,D′, less than 0.4, it is suggested that the parts be stacked in the discharge chute to increase the efficiency of the system. When the parts are stacked, the diameter of the discharge hole can be greater than the value obtained from Fig. (a). The top part in the stack should be about one part length below the top of the discharge hole.

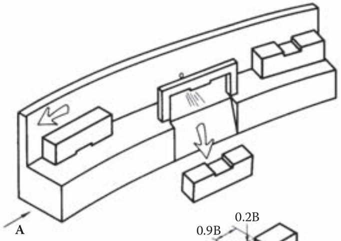
Example:

Given a part with L = 7.62 mm and D′ = 12.7 mm, then L/D′ = 0.6. From Fig. (a), d/D′ = 1.15 or d = 14.6 mm. Thus, an appropriate value for the diameter of the discharge hole III should be slightly less than 14.6 mm.

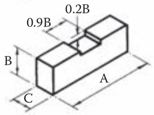
From Fig. (b), w/D′ = 0.27 or w = 3.43 mm. Thus, the width of the slot should be slightly less than 3.43 mm. The helical angle Θ = arctan (L/D′) = arctan (0.6) = 30.9°

AIR JET AND SILHOUETTE

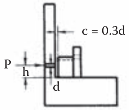
DEVICE CODE 1 9



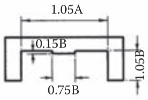
$\frac{B}{d} \simeq 4 \quad \frac{A}{B} > 3$



Part parameters



View in direction of arrow A



Silhouette

The air jet and silhouette device is used to feed and orient long rectangular parts with a through groove. A part traveling on the track with its longest side in the conveying direction and with the grooved side up will be blown through the silhouette back into the bowl by the air jet.

The important design parameters for the device are the air jet pressure P and the air jet height h.

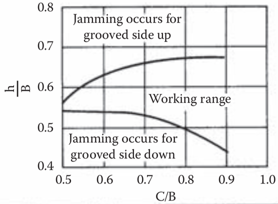
Example:

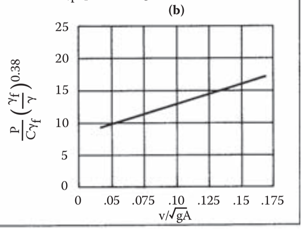
Rectangular aluminum parts (γ = 26.3 kN/m^3) 25.4 mm long × 8.5 mm high × 6 mm wide are to be fed with a conveying velocity of 50 mm/s. Thus C/B = 0.7, $v/\sqrt{gA}$ = 0.10, and from Fig. (a) the acceptable working range for h/B is between 0.525 and 0.664. Then, an appropriate value for h is 5 mm. From Fig. (b)

$$\frac{P}{C\gamma_f}\left(\frac{\gamma_f}{\gamma}\right)^{0.38} = 12.9 \times 10^4,$$

and therefore the required air jet pressure is 171.8 kN/m^2.

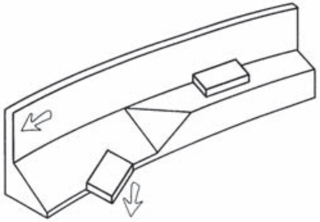
Nomenclature
P Pressure of air jet (kN/m^2)
v Mean conveying velocity (mm/s)
g Acceleraton due to gravity (9.81 m/s^2)
γ Specific weight of part (kN/m^3)
γ_f Specific weight of air (0.0119 kN/m^3)

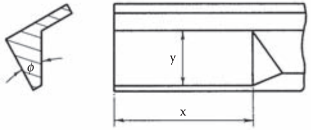




SLOPED TRACK

DEVICE CODE 2 0





Device parameters

The sloped track device is used to reject all parts back into the bottom of the bowl. It is used after devices such as the gap (Device Code #06) or silhouette (Device Code #13) which accept and discharge correctly oriented parts allowing parts in other orientations to pass over unaffected. These parts which pass are recycled to the bottom of the bowl using a sloped track.

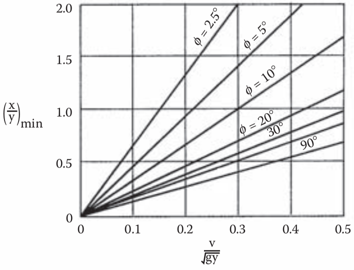
The important design considerations for this device are the relative length x and width y of the track for various slope angles ϕ these parameters are affected by the conveying speed and this information is given in the figure.

For example:

Suppose 20 mm long parts are to be rejected back into the bowl using a 20 degree sloped track which is 30 mm wide. If the parts are traveling at 100 mm/s along the horizontal track section, then

$$\frac{v}{\sqrt{gy}} = 0.18$$

From the figure, $(x/y)_{min}$ = 0.45 or x_{min} = 13.5 mm. This is the necessary clearance beyond the part length so that the actual value of track length is x_{min} plus the part length, or 33.5 mm.

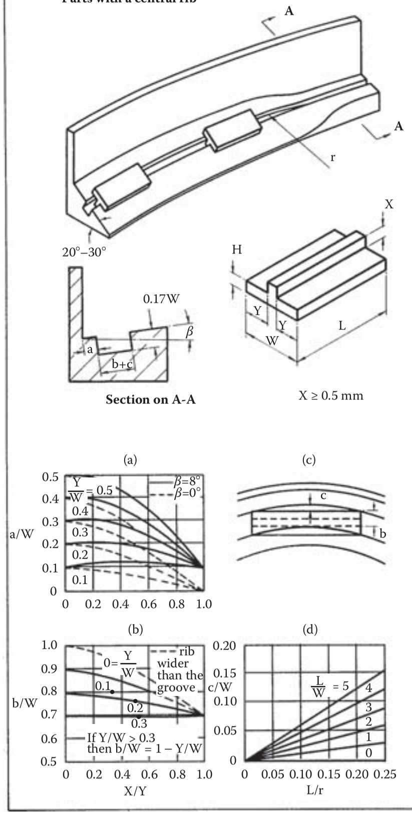


v = conveying speed
g = acceleration due to gravity (9.81 m/s^2)

SLOPED TRACK AND GROOVE

DEVICE CODE 2 2

Parts with a central rib



The sloped track and groove orienting device is used to feed and orient parts with ribs. The groove is located such that it remains a constant distance from the bowl wall. A ribbed part will pass through this device when traveling with its rib facing the track parallel to the conveying direction. All other parts will be rejected.

The groove width and location is set to reject all parts lying on their flat side and parts with their rib on the track but not parallel to the conveying direction. The distance to the outside edge of the groove a can be determined from Fig. (a).

Example:

Suppose W = 20 mm, Y = 8 mm, X = 3.2 mm and β = 8°, then Y/W = 0.4 and X/Y = 0.4. From Fig. (a), a/W = 0.36 and a = 7.20 mm.

The width of the groove b, neglecting the distance which compensates for bowl curvature c, can be determined from Fig. (b).

Example:

For the same part used in the previous example, Y/W = 0.4 and X/Y = 0.4 From Fig. (b), b/W = 0.6 and b = 12 mm.

The width of the groove including the distance which compensates for bowl curvature can now be found by adding c to b, as shown in Fig. (c). Values of c are obtained from Fig. (d).

Example:

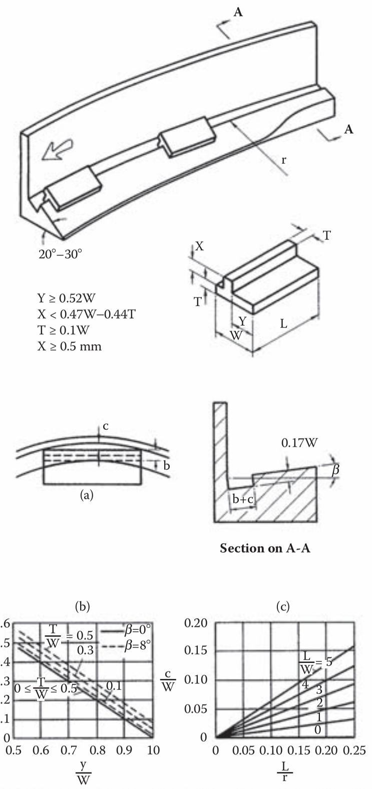
Suppose L = 40 mm, W = 20 mm and r = 200 mm, then L/W = 2.0 and L/r = 0.2. From Fig. (d), c/W = 0.05 and c = 1 mm. Adding c to b obtained from the previous example, the new groove width becomes 13 mm.

The depth of the groove is 0.17 W or 3.4 mm.

SLOPED TRACK AND GROOVE

DEVICE CODE 2 2

Parts with an offset rib



The sloped track and groove orienting device is used to feed and orient parts with ribs. The inside edge of the groove is located such that it remains a constant distance from the bowl wall. A ribbed part will pass through this device when traveling with its rib facing the track, parallel to the conveying direction and its narrower flange towards the bowl wall. All other parts will be rejected.

The groove width is set to reject parts lying on their flat side, parts with their rib not parallel to the conveying direction and parts with their wider flange towards the bowl wall. The bowl wall is the outside edge of the groove. The width of the groove b, neglecting the distance which compensates for bowl curvature, can be found in Fig. (b).

Example:

Suppose W = 20 mm, Y = 14 mm, T = 6 mm, and β = 0°, then Y/W = 0.7 and T/W = 0.3. From Fig. (b), b/W = 0.3 and b = 6 mm.

The width of the groove can now be found by adding the distance which compensates for bowl curvature c to b, as shown in Fig. (a). Values for c can be found in Fig. (c).

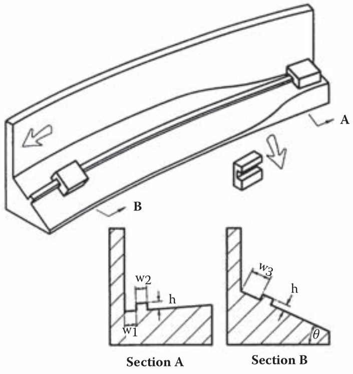
Example:

Suppose L = 40 mm, W = 20 mm and r = 200 mm, then L/W = 2.0 and L/r = 0.2. From Fig. (c), c/W = 0.05 and c = 1 mm. Adding c to b obtained from the previous example, the new groove width becomes 7 mm.

The depth of the groove is 0.17 W or 3.4 mm. Parts must not be able to stand upright on their rib.

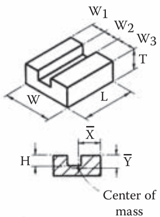
SLOPED TRACK AND RAIL

DEVICE CODE 2 4

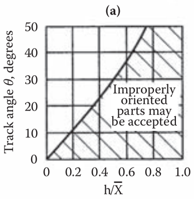


Section A **Section B**

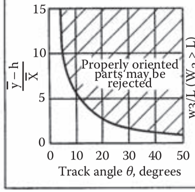
Device parameters



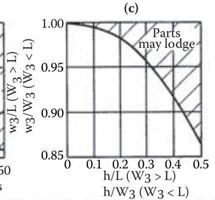
Part parameters



(b)



(c)



The sloped track and rail orienting device is used to feed and orient parts with either an offset or centered groove. Parts traveling with the groove down and parallel to the feed direction pass through the device when the rail is in the groove.

For a chosen rail height h less than or equal to the groove height H, the necessary track angle *q* to assure rejection of all parts with the groove facing up is determined from Fig. (a). Figure (b) is used to determine whether properly oriented parts will feed along the track without falling off, for a specific track angle and rail height.

To prevent jamming, the rail width w_2 must be less than the part groove width W_2 and is given by

$$w_2 = W_2 - 0.02L \quad \textbf{(1)}$$

At the rail entrance (section A) the distance of the rail from the wall w_1 is given by

$$w_1 = W_1 + 0.02L \quad \textbf{(2)}$$

To prevent improperly oriented parts from jamming, the maximum distance from the wall to the rail w_3 (section B) is found from Fig. (c).

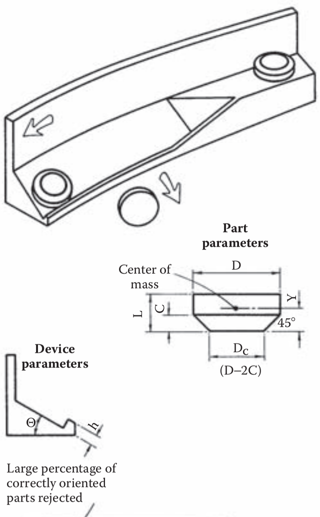
Example:

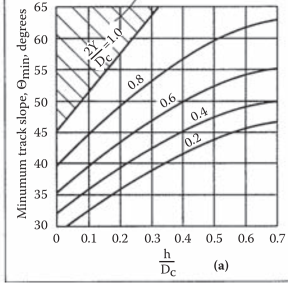
Given a part with dimensions W = 20 mm, L = 40 mm, W_1 = 5 mm, W_2 = 5 mm, W_3 = 10 mm, H = 5 mm and thickness T = 10 mm, then by geometry $\overline{X}$ and $\overline{Y}$ are 9.6 mm and 5.4 mm, respectively. For a chosen rail height h = H = 5 mm, $h/\overline{X} = 0.52$ and from Fig. (a) $\theta \geq$ 31° (0.5 4 rad).

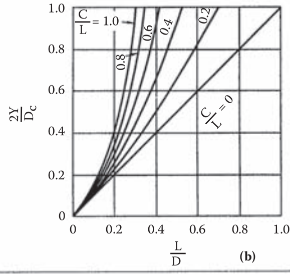
With $(\overline{Y} - h)/\overline{X} = 0.042$ and $\theta =$ 31° Fig. (b) shows that properly oriented parts will not be rejected. From Equation (1) w_2 = 4.2 mm and from equation (2) w_1 = 5.8 mm. Since $W_3 < L$ and $h/W_3 = 0.5$ then from Fig. (c) $w_3/W_3 \leq 0.87$ or $w_3 \leq$ 8.7 mm.

SLOPED TRACK AND LEDGE

DEVICE CODE 2 5







The sloped track and ledge orienting device is used to reject a chamfered part traveling chamfered end down while accepting a part traveling chamfered end up.

The important design parameters of the device are the ledge height h and the angle of track slope Θ. The magnitude of these design parameters can be determined from a knowledge of the part parameters and Fig. (a) for any chamfered part.

The device operates effectively, rejecting all the unwanted orientations and accepting all the wanted orientations when the distance Y of the center of mass of the part from the chamfered end is less than half the diameter of the chamfered end D_c, and if the ledge height h is less than the chamfer height C.

For discs with a 45° chamfer the locations of the center of mass can be found from Fig. (b) knowing the length L and major diameter D of the disc as well as the chamfer length C.

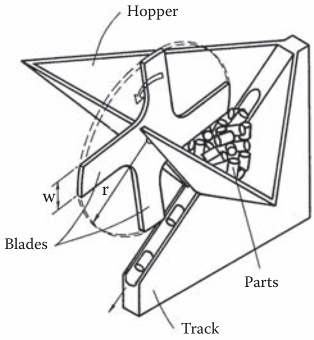
Example:

Given a chamfered disc with dimensions D = 25 mm, L = 10 mm, C = 5 mm, then D_c = 15 mm.
Since L/D = 0.4 and C/L = 0.5
then from Fig. (b)
$2Y/D_c = 0.78$
If h = 3 mm, then $h/D_c = 0.2$ and
From Fig. (a)
$\Theta_{min} = 49°$

D.4 NONVIBRATORY FEEDERS

Catalog of the various types of nonvibratory feeders with general design data.

BLADED WHEEL HOPPER FEEDER



Suitability

Cylindrical parts, spherical parts, disc shaped parts such as nuts, washers, etc.

Principle

The rotating bladed wheel is used to agitate the parts so that they tend to fall into the track and slide out of the hopper in the desired orientation.

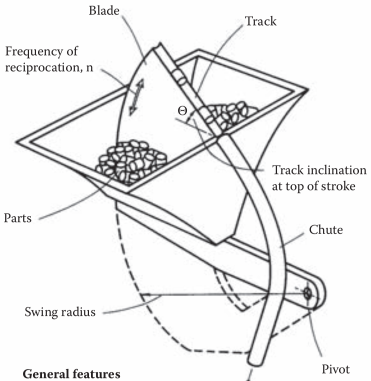
General features

The track is arranged so that it is tangent to the circle generated by the tips of the rotating blades at the point where the blades enter the hopper.

General data

Angle of inclination of the track = 0.79 rad (45°)
Number of blades in the wheel = 4–6
Blade width to length ratio, $w/r = 0.3$
Maximum linear velocity of the blade tip = 0.70 m/s

CENTERBOARD HOPPER FEEDER


Blade
Track
Frequency of reciprocation, n
Θ
Track inclination at top of stroke
Parts
Chute
Swing radius
Pivot

Suitability

Cylindrical parts, discs, headed parts.

Principle

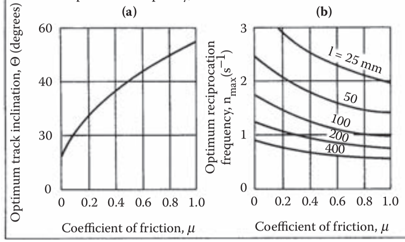
The blade reciprocates up and down through the mass of parts picking up those parts which are in the proper orientation. The track on the blade is designed to suit the particular part. The motion of the blade also serves to agitate and reorient those parts remaining in the hopper during each stroke. The blade dwells at the top of the stroke to allow time for parts to slide down the track and into the delivery chute.

General features

The motion of the blade can be controlled by a cam or a pneumatic piston with the cam being preferable since it controls the blade's deceleration. A piston would need appropriate springs or shock absorbers as well as flow control valves to adequately control the deceleration of the blade, particularly at the top end of the stroke, to avoid having parts fly off the track.

For ease in estimating the maximum reciprocation frequency, the motion of the blade on the up stroke is assumed such that the acceleration is constant for the first half of the up stroke and equals the deceleration during the second half of the up stroke. The dwell is long enough to allow a part to slide the entire length of the track I and the inclination angle Θ is optimized to maximize the reciprocation frequency. The time of the return stroke is considered equal to the time of the up stroke.

The swing radius is twice the track length.

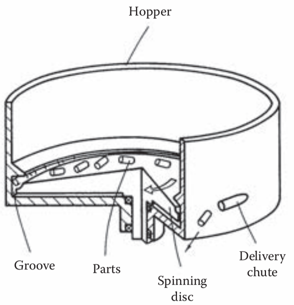


General data

Example:

The coefficient of friction between the part and the track is 0.4 and the track length is 200 mm. From Fig. (a), the optimum inclination angle of the blade at the top of the stroke is 36 degrees and from Fig. (b), the maximum reciprocation frequency is $0.9\ s^{-1}$.

CENTRIFUGAL HOPPER FEEDER



Suitability

Cylinders with L/D > 2.0. Parts must not be fragile.

Principle

A horizontal disc spins inside a shallow cylindrical hopper. Bulk separation is accomplished by centrifugal action. Parts are carried around the perimeter until they are deflected into a delivery chute which is located tangent to the stationary hopper wall.

General features

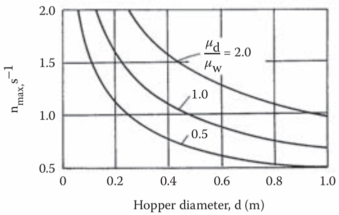
This hopper feeder is capable of a wide range of feed rates. The spinning disc has a slight conical shape to aid separation at lower speeds. A groove eliminates all but the desired orientations.

General data

An upper limit to the feed rate occurs when the friction force between the part and the stationary hopper wall equals that between the part and the spinning disc. This upper limit can be determined from the graph.

Example

If $\mu_d = \mu_w = 0.45$ and the hopper diameter d = 0.4 m, then $\frac{\mu_d}{\mu_w} = 1.0$ and from the graph $n_{max} = 1.1\ s^{-1}$ (66 rpm).

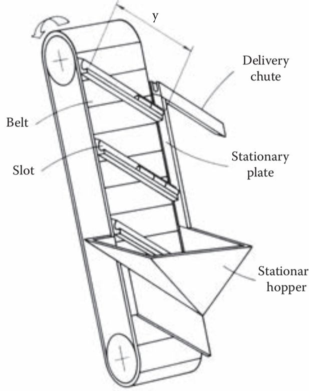


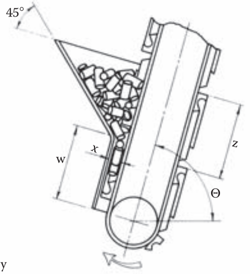
n_{max} = maximum rotational frequency of the disc

μ_d = coefficient of friction between the part and the spinning disc

μ_w = coefficient of friction between the part and the statonary hopper wall

ELEVATOR HOPPER FEEDER



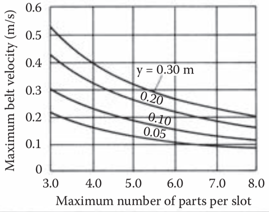


Side view

Suitability:
Spherical parts and parts which have end-to-end symmetry such as cylinders or square prismatic parts.

Principle:
A continuous, flexible belt on the elevator has a series of ledges or slots and turns through a stationary hopper so that parts in the hopper tend to fall onto the slots on the belt. A stationary plate along the side prevents the parts from sliding out of a slot until the parts reach the delivery chute near the top of the feeder.

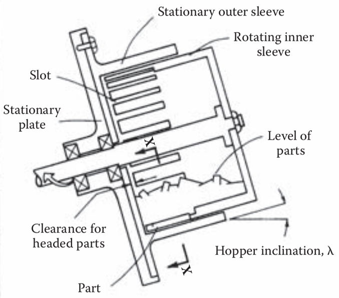
General features:
The length of the lower part of the hopper w, must be greater than the distance between adjacent slots z. To avoid jamming, the distance x between the lower section of the hopper and the belt should be about 1.2 times the width of the parts.

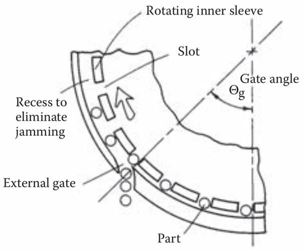


General data:
Angle of hopper side = 45° (.79 rad)
Belt inclination angle, Θ = 75–85° (1.31–1.48 rad)
The maximum velocity of the belt can be determined from the graph.

Example:
If the length of a slot y = 100 mm and the part length is 20 mm then the maximum number of parts per slot is 5 and from the graph the maximum belt velocity is 0.18 m/s.

EXTERNAL GATE HOPPER FEEDER





Section on X-X

Suitability:
Cylindrical parts
Headed parts such as rivets and screws

Principle:
The rotating sleeve having slots in its wall rotates inside the stationary outer sleeve. Properly oriented parts will nest in the slots against the stationary outer sleeve. At some point the slots pass the gate in the stationary outer sleeve, which allows the parts to escape one-by-one into the delivery chute.

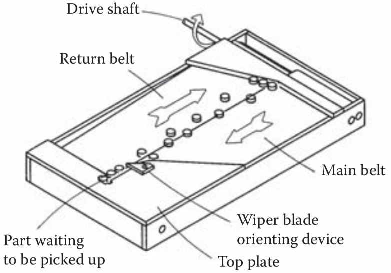
General features:
The position of the external gate and the inclination of the hopper axis are denoted by the gate angle (Θ_g) and the hopper inclination (λ) respectively. Both the gate angle and the hopper inclination can be varied to optimize feeding for a particular part. Usually the optimum gate angle is between 45 and 65 degrees. With very high gate angles parts do not have sufficient time to fall from the slots into the delivery recess while with very low gate angles the parts do not have sufficient opportunity to become oriented in the slots. The hopper is given a slight inclination, usually between 10 and 15 degrees, to guide the parts towards the slots. However, if the hopper inclination is too large jamming can occur between the inner rotating sleeve and the stationary outer sleeve; also the opportunity for parts to fall into the slots is reduced.

The recess in the wall of the stationary outer sleeve above the gate is provided to minimize the possibility of jamming as parts pass through the gate.

As the complete elimination of the jamming of parts is usually difficult, the drive mechanism should be designed so that it stops whenever a jam occurs, moves in the opposite direction until the jam is cleared, and then continues proper operation.

General data:
Maximum peripheral velocity: 0.5 m/s
Gate angle: Θ_g = .79–1.13 Rad. (45–65 degrees)
Hopper inclination: λ = .17–.26 Rad. (10–15 degrees)

HORIZONTAL BELT FEEDER



Suitability:

A wide range of parts including fragile parts, cyclindrical parts, square or rectangular prismatic parts, disc shaped parts such as washers, nuts, etc.

Principle:

The main belt carries parts past orienting devices to a pocket. Parts which are incorrectly oriented are rejected on to a return belt which recirculates the parts.

General features:

The belts are driven in opposite directions by a continuous drive. The return belt has a slightly higher velocity than the main belt.

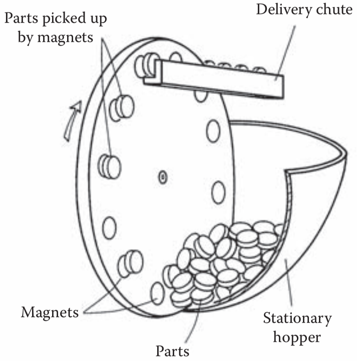
The feeder can be easily modified to feed various parts by changing the top plate.

A step between the belts must be provided at the delivery end. This step facilitates the reorientation of incorrectly oriented parts.

General data:

Typical velocity of main belt = 25 mm/s

MAGNETIC DISC HOPPER FEEDER



Suitability

Nuts, discs with L/D less than .7, prisms of square cross section with L/D less than 3.0. Extremely thin parts or parts without large flat surfaces are difficult to feed. Parts must be ferromagnetic. The feeding action is gentle.

Principle

The rotating disc, with magnets mounted in its surface, turns inside a hopper. Parts become attached to the magnets and are carried by the rotating disc until they reach the delivery chute where they are detached from the magnets and guided down the chute. Parts attached to the magnets in incorrect orientations are returned to the hopper.

General features

Optimum load generally fills one third of the hopper volume. Magnets should have a holding capacity of 10–20 times the weight of one part and have a diameter approximately equal to the major dimension of the part.

General data

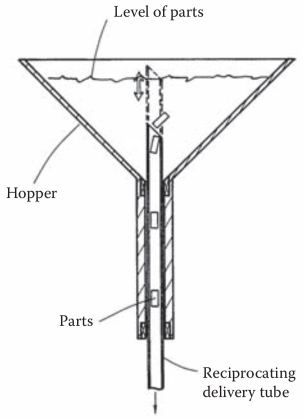
Angle of inclination of rotating disc from vertical = 0 to 0.7 rad (0 to 40°) for nuts and prisms, 0.7 rad (40°) for discs

Angle of inclination of delivery chute = 0.79 rad (45°)

Linear velocity of magnets = 0.08 – 0.24 m/s

Maximum number of magnets $= 0.5 \times \dfrac{\text{diameter of rotating disc}}{\text{magnet diameter}}$

RECIPROCATING TUBE HOPPER FEEDER



Suitability

Spheres, cylinders with L/D less than 4.0, discs with L/D less than .7, prisms of square cross section with L/D less than 3.0. Other regular cross section prisms may also be fed. Feeder action can damage delicate parts.

Principle

The reciprocating delivery tube passes up and down through a cubical hopper. Correctly oriented parts will enter the opening at the top of the delivery tube. The reciprocating delivery tube also serves to agitate the parts.

General features

Optimum hopper load is that which fills half the volume of the hopper, and the reciprocating delivery tube should rise just above the maximum level of parts in the hopper. The inside silhouette of the delivery tube must be designed to accept only correctly oriented parts one at a time.

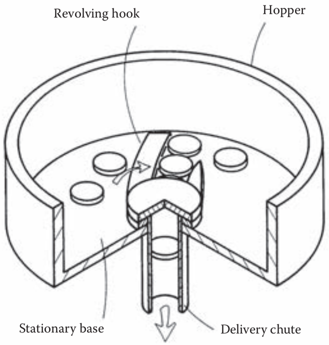
General data

Hopper cone angle = 1.57 rad (90°)

Angle of top of reciprocating delivery tube = .79 rad (45°)

Maximum linear velocity of reciprocating delivery tube = 0.60 m/s

REVOLVING HOOK HOPPER FEEDER



Suitability:

Flat disc shaped parts, such as washers L/D < 0.2.

Principle:

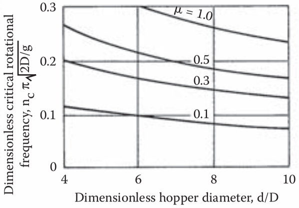
The revolving hook rotates above the stationary base of the hopper. The parts are guided along the inside curve of the hook to the center hole of the stationary base and drop into the delivery chute, end-to-end.

General features:

The thickness of the revolving hook is the same as that of the parts. A wiper, having a tapered outside edge, and the hook form a passage whose width is less than 2D. A hood is attached to the hook above the center hole so that parts from above do not block the delivery chute. The combination of delivery chute, hook and wiper rotate together.

General data:

The profile of the hook is the same as that of the stationary hook in a stationary hook hopper feeder for a coefficient of friction between the part and the hook of 0.5. In this design the radius of the hole is equal to the radius of the part. Generally, the parts should fill half the hopper. A drastic reduction in the feed rate occurs when the rotational frequency of the hook approaches the critical rotational frequency given in the graph below.

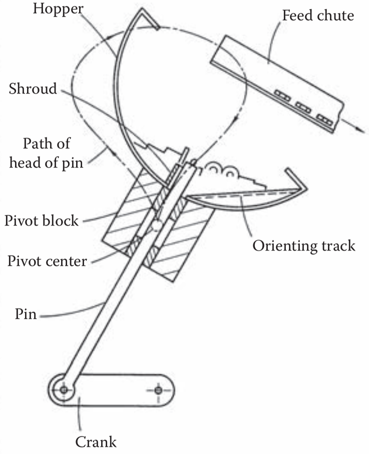


Example:

If D = 30 mm, d = 240 mm and μ = 0.4, then d/D = 8 and from the graph $n_c \pi \sqrt{2D/g} = 0.17$. The critical rotational frequency n_c is 0.69 s^{-1} (42 rpm).

n_c = Critical rotational frequency
d = Hopper diameter
D = Part diameter
μ = Coefficient of friction between the part and the stationary base
g = 9810 mm/s^2

ROCKING TROUGH HOPPER FEEDER



Suitability

This feeder is specifically designed for feeding both plain and spring washers. Disc-shaped parts with an inside hole such as nuts can also be fed. This feeder is most suitable when more than one stream of parts is required. In this case the hopper would be in the form of a long trough and a common crank shaft would drive several pins.

Principle

The crank drive which rotates at a constant rate, actuates the pin which in turn rocks the hopper mounted on the top of the pivot block. As it rises the pin selects one component and places it in the delivery chute.

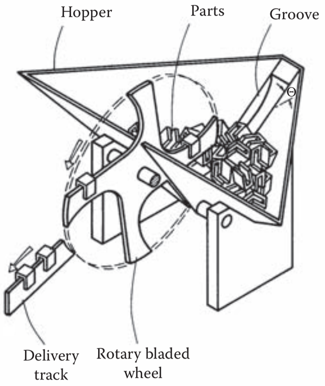
General features

The driving mechanism must be a continuous drive. The hopper is in the form of a trough with closed ends, the bottom of which is formed to a radius extending to at least 45 degrees (0.8 rad.) either side of the center. An orienting track on one side and a shroud on the other side of the nest provided in the hopper help to orient the components. The head of the pin is machined to accept one component at a time.

General data

Typical rotational frequency of crank = 0.5 s^{-1} (30 rpm)

ROTARY CENTERBOARD HOPPER FEEDER



Suitability:

U-shaped parts.

Principle:

The rotary bladed wheel agitates the parts causing some to fall into the shaped groove in the hopper bottom in the correct orientation. As the wheel continues to rotate some of the parts are collected by the blades and raised clear of the batch of parts. These oriented parts slide along the blade and onto the delivery track when the blade and track are aligned.

General features:

To avoid jamming, the clearance between the blade and the hopper groove should be less than half the thickness of the part. The edges of the blade should be profiled to allow correctly oriented parts to slide along the blade and onto the delivery track. The groove width should be approximately 1.1 times the width of the parts. The upper end of the groove is curved so that parts can be recirculated back into the hopper. The driving mechanism can be either a continuous drive or an intermittent drive such as a geneva mechanism.

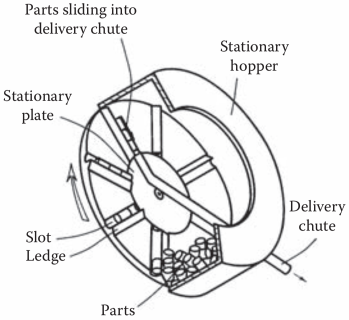
General data:

Groove inclination $\Theta = 0.79$ rad (45°)

Number of blades in the rotary bladed wheel = 4–6

Maximum peripheral velocity of the rotary bladed wheel = 0.6 m/s

ROTARY DISC HOPPER FEEDER



Suitability

Cylindrical parts, spherical parts, disc shaped parts such as nuts, washers, etc.

General features

The driving mechanism can be a continuous or indexing drive.

Principle

The rotary disc, with slots machined radially in its face, turns inside a hopper. The ledges below the slots agitate the parts so that they fall in the slots. A stationary plate prevents the parts from sliding out of a slot until the slot reaches its uppermost position when the parts slide into the delivery chute.

General data

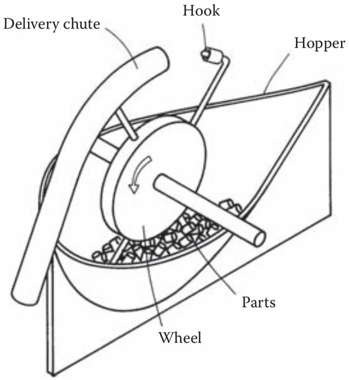
Angle of inclination of disc = .96 – 1.05 rad (55°–69°)

Angle of inclination of the delivery chute = 0.61 rad (35°)

Maximum operating speeds for a hopper 400 mm dia. are:

for continuous drive = 0.08 s^{-1} (4.8 rmp)
for Geneva type indexing drive = 1 slot/s

ROTARY HOOK HOPPER FEEDER



Suitability

Tubular parts, cup shaped parts.

Principle

The hooks on the rotating wheel agitate the parts and select them by entering the open end. After a hook passes its hightest point, the part falls from the hook into the delivery chute.

General features

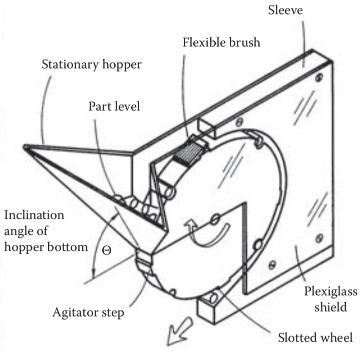
To avoid parts jamming beteen the hopper and the hook, it is necessary that the bottom of the hopper and the path of the rotating hook have the same center of curvature. To prevent parts jamming between the hopper and the wheel, the diameter of the rotating wheel should be sufficiently small so that there is at least one part length clearance between the hopper and the wheel. The feeder can handle rotational parts with a L/D ratio between 1 and 4. the ratio between the diameter of the hook and the inner diameter of the part should be approximateldy 0.6.

General data

Number of hooks on the rotating wheel = 4–8

Typical linear velocity of the hook tip = 0.3–0.5 m/s

SLOTTED WHEEL HOPPER FEEDER



Suitability:

Long slender parts which have end-to-end symmetry (alpha symmetric) such as cylinders or square prismatic parts.

Principle:

The rotating wheel, with slots machined in its periphery, turns through a stationary hopper so that parts tend to fall into the slots. Incorrectly oriented parts or excess parts which enter the slots are removed by a brush located at the top of the feeder. Correctly oriented parts are retained in the slot by a sleeve until they reach the delivery chute at the bottom of the device.

General features:

The drive should be continuous and capable of supplying a torque sufficient to move the slots through the mass of parts and the rejection brush mechanism.

The hopper should have vertical walls at the sides of the wheel in order to align the part with the slot. The inclination angle of the hopper bottom, Θ, has no effect on the part feed rate. For long parts, small steps on the wheel periphery are needed to agitate the parts in the hopper.

The performance curves for this feeder, which are shown in the data sheets in Section 2 represent the situation where the length of the slot is such that more than one correctly oriented part can be accomodated in each slot. When the ratio of te length of the slot to the part length is 1.8 then an efficiency of approximately 0.75 parts per slot is obtained.

General data:

Maximum peripheral velocity = 20 mm/s

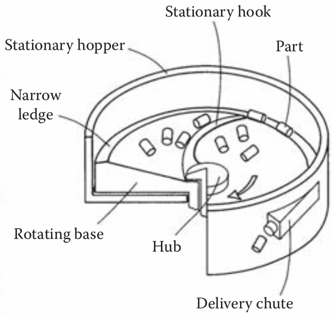
Number of slots (wheel diameter = .3 m) = 4–6

Agitator step height for cylindrical parts = .05 × part diameter

Agitator step height for square prisms = .03 × width of the prism

Minimum peripheral force = 4.5N (1 lbf)

STATIONARY HOOK HOPPER FEEDER



Suitability:

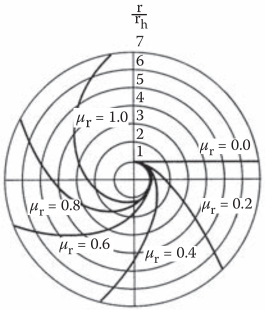
This feeder is especially suitable for handling fragile cylindrical and headed parts.

Principle:

The rotating base turns inside the stationary hopper. When the parts come in contact with the leading edge of the stationary hook they are guided to the periphery of the disc, carried around and finally deflected into the delivery chute, which is connected to the stationary hopper wall.

General features:

The rotating disc is dished so that parts will accumulate near the center of the hopper. The stationary hook is designed so that its shape will result in a part being delivered at constant velocity along the hook. A continuous drive mechanism is used.



General data:

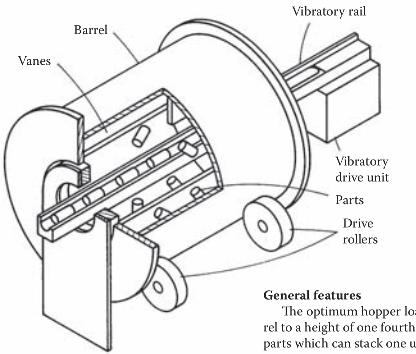
The shape of the hook is chosen from the figure which shows the profile of the hook for various values of the coefficient of friction between the part and the hook μ_r.

r_h = Radius of hub

r = Radial location of particular point on hook

Maximum peripheral velocity, 0.4 m/s

TUMBLING BARREL HOPPER FEEDER



Suitability

A wide variety of parts, such as cylinders, spheres, U-shaped parts, angled parts, and prisms.

Principle

As the barrel shaped hopper rotates, parts are lifted by the vanes and thrown onto the rail. Vibration of he rail causes parts to be conveyed out of the barrel. The rail should be shaped to allow only properly oriented parts to be fed out of the barrel.

General features

The optimum hopper load is that which fills the barrel to a height of one fourth the inside diameter. For parts which can stack one upon another it is necessary to provide the outlet with a stationary gate which outlines the shape of a part on the rail so that parts come out in a single layer only. Rubber or cork may be placed along the inside wall of the barrel to reduce noise and part damage.

General data

For a part where motion relative to the vanes is one of pure translation (part does not roll), the rotational frequency which maximizes the number of parts that land on a rail passing through the barrel center can be determined from Fig. (a). The result may not be valid for parts whose motion relative to the vanes contains rotational components.

Figures (b) through (e) can be used to estimate the values of the barrel design parameters that achieve a given feed rate. To use the graphs it is first necessary to determine, by observation, the average number of parts per vane, P, which land on an empty rail.

Example: (Nomenclature is defined on the following page)

Parts with L = 10 mm are to be fed at the rate of one per second using a barrel of dimensions l_b = 200 mm, d = 150 mm, I = 30 mm. Four radial vanes are used and α = 0, N = 4, and μ = 0.4.

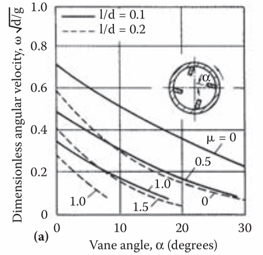
The ratio l/d = 0.2. Thus, from Fig. (a), $\omega\sqrt{d/g}$ is 0.43. Hence, the required angular velocity ω is 3.48 rad/s (33 rpm).

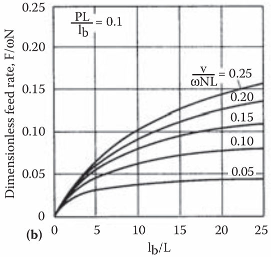
Assuming that by observation P = 4, then with $l_b/L = 20$, $PL/l_b = 0.2$. The dimensionless vlocity, v/ωNL, can be determined for a desired dimensionless feed rate, F/ωN. For a feed rate of one part per second, F/ωN = 0.07 and from Fig. (c). v/ωNL = 0.075 so that v = 10.4 mm/s.

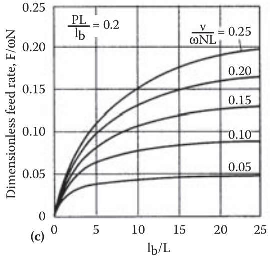
TUMBLING BARREL HOPPER FEEDER (Continued)

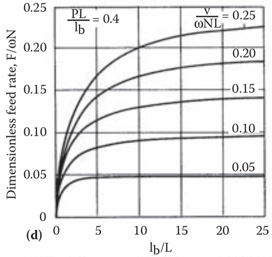
Nomenclature

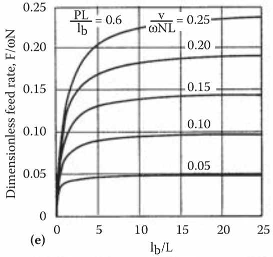
d = Barrel diameter
g = Acceleration due to gravity (9.81 m/s^2)
l = Width of the vanes
l_b = Barrel length
v = Conveying velocity of parts on the rail
F = Feed rate
L = Part dimension along rail
P = Number of parts per vane which land on the empty rail
N = Number of vanes
α = Vane angle (see Fig. (a))
μ = Coefficient of friction between the part and a vane
ω = Angular velocity of the barrel











Nomenclature

A = length of longest side of rectangular envelope; maximum track acceleration
A_f = average number of faults requiring rework for automatic insertion of electronic components
A_i = basic cost of one part
A_n = component of maximum track acceleration normal to the track
A_p = component of maximum track acceleration parallel to the track
B = length of intermediate side of rectangular envelope; rate of increase in cost of one part due to quality level
B_s = size of batch to be produced during equipment payback period
C = length of shortest side of rectangular envelope; capital cost of equipment, including overhead
C_a = cost of assembling one assembly
C_ai = cost of automatic insertion of electronic component
C_ap = programming cost per component for automatic insertion
C_as = setup cost per component type for automatic insertion
C_B = cost of transfer device per workstation or buffer space for a free-transfer machine
C_C = cost of work carrier
C_c = cost of replacement component
C_d = dimensionless assembly cost per part
C_e = total equipment cost for an assembly machine
C_F = cost of automatic feeding device and delivery track
C_f = cost of automatic part presentation; cost of feeding one part
C_gp = general-purpose equipment cost
C_i = automatic insertion cost for one part; cost of one part
C_M = cost of manually loaded magazine
C_mi = cost of manual insertion of one part
C_mm = cost of part presentation by manually loaded magazine
C_op = assembly operation cost for one electronic component
C_pr = average production (assembly) cost for one assembly
C_r = relative feeder cost
C_ri = cost of robot insertion of electronic component
C_rp = programming cost per component for robot insertion
C_rs = setup cost per component type for robot insertion
C_rw = average rework cost for electronic component
C_sp = special-purpose equipment cost
C_T = cost of transfer device per workstation for an indexing machine
C_t = total cost of each assembly produced, including the cost of parts
$C_{t(\mathrm{min})}$ = minimum total cost of the completed assembly
C_W = cost of workhead

D = diameter of part; diameter of hole; track depth; proportion of downtime on assembly machine

D_h = diameter of rivet head

E = efficiency of feeder; modified efficiency of feeding system; orienting efficiency

E_{ab} = energy barrier in moving a part from orientation *a* to orientation *b*

E_{ba} = energy barrier in moving a part from orientation *b* to orientation *a*

E_{ma} = manual assembly efficiency

E_o = factory overhead ratio for equipment

F = frictional resistance or force; feed rate

F_m = minimum unrestricted feed rate (that is, the unrestricted feed rate when bowl is full); maximum feed rate for one feeder

$F_{\max}$ = maximum feed rate

F_r = required feed rate

FR_s = feed rate per slot for an external gate hopper

H = height the part hops on the track

J = effective distance the part hops on the track

J_0 = J/R

L = length of part; insertion depth

L_1 = length of horizontal track section

L_2 = length of straight inclined track section

M = cost of operating a machine per unit time if only acceptable assemblies are produced

M_f = average number of faults requiring rework for manual insertion of electronic components

M_t = total cost of operating a machine per unit time, including operator's wages, overhead, actual operating costs, machine depreciation, and cost of dealing with unacceptable assemblies

N = normal force; number of vanes; number of parts in hopper; number of assemblies

N_a = number of parts in aspect *a*

N_b = number of parts in aspect *b*; number of parts below lower sensor and acceptable level; number of boards per panel in manufacture of PCBs

N_ℓ = number of pins or leads on one electronic component

$N_{\min}$ = theoretical minimum number of parts in an assembly

N_p = number of parts delivered per blade, cycle, slot, or revolution; number of parts held in feed track

N_{set} = number of setups for manufacture of PCBs

N_{tech} = minimum number of technician personnel required to correct faults

P = number of parts per vane falling on empty rail

P_a = production rate of acceptable assemblies; probability for aspect *a*; probability for orientation *a*

P_b = probability for aspect *b*; probability for orientation *b*; equipment payback period (months)

P_e = assembly plant or assembly worker efficiency

P_s = number of shift-years during equipment payback period

P_u = number of unacceptable assemblies produced per unit time

Q_e = equivalent cost of one operator on one shift in terms of capital equipment

R = partition ratio $P_a/(P_a + P_b)$; radius of gravity feed track; radius of base of truncated cone; radius of track
R_e = probability that a part will be rejected
R_f = rate for one automatic feeder; average number of faults requiring rework for robot insertion of electronic components
R_i = rate for one automatic workhead
R_p = number of parts, operations, or components
S_n = number of shifts
T = downtime due to one defective part
T_{rf} = average time to rework one electronic component per lead or post
V_a = annual production volume
V_s = annual production volume per shift
W = weight of part, width of part
W_a = assembly worker rate
W_c = relative workhead cost
W_r = ratio of cost of all personnel to the cost of one manual assembly worker
W_t = total rate for all personnel engaged on an assembly machine
W_{tech} = rate for one technician to correct faults
a = linear acceleration of part
a_n = normal component of amplitude of track vibration
a_0 = amplitude of track vibration
a_p = parallel component of amplitude of track vibration
a_s = center distance between slots of external gate hopper
b = distance from the apex of the V-cutout orienting device to the bowl wall; size of buffer storage between workheads on a free-transfer machine
b_0 = b/R
b_t = track width
b_u = largest value of b_0 for which all the unwanted orientations of a truncated cone are rejected
b_w = smallest value of b_0 for which all the wanted orientations of a truncated cone are accepted
c = clearance; dimensionless clearance
d = hopper diameter; barrel diameter; downtime on workhead due to faulty parts when N assemblies are produced; diameter of screw head
d_t = minimum track diameter
f = frequency of vibration
g = acceleration due to gravity
g_n = component of g normal to the track
h = depth of screw head
h_g = gap between cylinder and sleeve in external gate hopper
j = distance as defined in Figure 3.38 and Figure 3.39
j_0 = j/R
ℓ = length of part; length of slot; length of track; width of vanes; distance from the screw head bottom to the center of mass
$\bar{\ell}$ = average part length
ℓ_b = length of barrel
m = proportion of defective parts causing a machine fault, mass of part
m_p = mass of part
m_1 = part mass per unit length

n = reciprocation frequency; rotational frequency; number of parts to be assembled in one assembly; number of parts to be automatically assembled
n_{a} = number of parts assembled manually per machine cycle
n_{c} = critical rotational frequency
n_{f} = average number of parts fed during one workhead cycle with a 100% efficient feeder
n_{max} = maximum reciprocation frequency; maximum rotational frequency
n_{r} = maximum number of parts assembled at one robot station
n_{s} = economic number of stations tended by one technician; number of standard deviations
$n_{s\ \mathrm{max}}$ = maximum number of stations tended by one technician
n_t = number of robot stations on one machine
p = $[2 + (y/x^2]^{1/2}$
q = $[1 + (y/x^2]^{1/2}$
r = radius from center of hopper; blade radius; radius of the top of a truncated cone; radial position
r_b = centerboard hopper swing radius
r_h = radius of hopper hub
r_0 = r/R
s = slot width; shank diameter
t = time; cycle time of assembly workhead; average assembly time per part assembled for a programmable workhead or robot; diameter on top of screw head
t_a = manual assembly time for one part (handling and insertion)
t_{at} = assembly machine or station cycle time
t_c = time taken by operator to dismantle an unacceptable assembly
t_f = total period of feeder cycle
t_h = handling time for one part
t_i = time for index; manual insertion time
t_m = manual assembly time
t_{ma} = total manual assembly time for one assembly
t_p = time for a part to move one part length;
t_{pr} = average production (assembly) time for one acceptable assembly
t_{pw} = additional handling time due to part weight
t_q = required average production time
t_s = time taken for parts to slide from slot of rotary-disk hopper feeder
t_w = workhead cycle time
t_1 = time to lift blade of centerboard hopper
t_2 = dwell time for blade of centerboard hopper
v = peripheral velocity of sleeve in external gate hopper; velocity of part; conveying velocity
v_m = mean conveying velocity
w = width of blade
x = half-width of a square prism; ratio of defective to acceptable parts
x_{opt} = optimum ratio of defective to acceptable parts giving minimum total cost of the completed assembly
y = half-length of a square prism

α = alpha rotational symmetry angle of part; vane angle; inclination angle of gravity feed track; angle between screw axis and a line normal to the track; cost ($1/D$)

α_1 = arc sin ($1/q$)

α_2 = arc sin ($1/p$)

β = beta rotational symmetry angle of part; arc tan (x/y); friction angle

β_w = wiper blade jamming angle

γ = riser angle; phase angle

η = efficiency of bowl feeder orienting system

θ = track angle; inclination of delivery chute; inclination of elevator hopper; half-angle of the V-cutout orienting device

θ' = inclination of disk in rotary-disk feeder

θ_m = maximum inclination of track

θ_T = critical track angle where screw just touches track cover (or tilt angle)

θ_w = angle between the wiper blade and the bowl wall

λ = hopper inclination for external gate hopper

μ = effective coefficient of friction

μ_b = coefficient of dynamic friction between part and spinning disk

μ_d = coefficient of dynamic friction

μ_{max} = maximum value of coefficient of static friction for sliding to occur

μ_p = coefficient of dynamic friction between part and moving surface

μ_r = coefficient of dynamic friction between part and hook

μ_s = coefficient of static friction

μ_w = coefficient of dynamic friction between part and hopper wall

ϕ = angle of hopper wall

ϕ_g = gate angle for external gate hopper

ψ = vibration angle

ψ_{opt} = optimum vibration angle

ω = angular frequency of vibration; angular velocity

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